Sustainable
Food Technology

REVIEW

Cite this: *Sustainable Food Technol.*, 2024, **2**, 1297

Advancements in sustainable food packaging: from eco-friendly materials to innovative technologies

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The demand for sustainable food packaging solutions has escalated in response to growing environmental concerns and consumer preferences for eco-friendly products. This review delves into the realm of sustainable food packaging materials and methods, exploring their necessity, applications, and impact on advancing sustainability goals. The review begins by examining commonly used materials in food packaging and their negative environmental impacts, particularly focusing on issues like pollution and non-biodegradability. It then highlights the urgent need for eco-friendly alternatives, emphasizing the necessity to transition towards sustainable materials to mitigate ecological harm. A historical timeline contextualizes the evolution of food packaging materials, leading into an exploration of various sustainable options, from general examples to advanced technologies like bio-nanocomposites and antimicrobial packaging. Greener fabrication processes and recent advancements in sustainable materials are highlighted, showcasing innovative approaches such as hybrid nanoparticle coatings and multifunctional bio-nanocomposite films. Furthermore, the review discusses the role of chemical methods in improving packaging properties and examines recent developments in sustainable food packaging, including allicin-loaded nanofibrous films and humidity-adjustable gelatin hydrogel films. The concluding remarks emphasize the significance of these advancements in mitigating environmental impact and enhancing food safety, while also outlining future outlooks for continued innovation in sustainable food packaging.

Received 19th March 2024
Accepted 30th June 2024

DOI: 10.1039/d4fb00084f

rsc.li/susfoodtech

Sustainability spotlight

In a world where sustainability is paramount, the quest for eco-friendly solutions in every aspect of our lives, including food packaging, has gained significant momentum. Our review aims to shed light on the diverse array of sustainable food packaging materials available today, evaluating their environmental impact, functionality, and potential for widespread adoption. We delve into the realm of sustainable food packaging materials, exploring innovations ranging from biodegradable polymers derived from renewable resources to compostable alternatives that minimize environmental harm. By critically assessing the life cycle analysis, carbon footprint, and recyclability of these materials, we offer insights into their efficacy in mitigating the ecological footprint of food packaging. Through our comprehensive review, we illuminate the path towards a more sustainable future for food packaging, where innovative materials harmonize with environmental stewardship, paving the way for a greener, healthier planet.

1. Introduction

Amidst a rapidly growing global population and increasing urbanization, the significance of food packaging has grown exponentially. This sector represents an ever-evolving industry constantly pressured to innovate and deliver more efficient solutions. Serving as a crucial barrier against external factors and microbial contamination, food packaging ensures the safe and reliable delivery of consumables to consumers. Consequently, the processed food industry places significant emphasis on the development of packaging materials with desirable traits such as appealing aesthetics, hygienic properties, durability, and eco-friendliness. Despite the prevalence of plastics due to their lightweight nature, impermeability to gases and moisture, cost-effectiveness, and transparency, their use poses a range of drawbacks including non-biodegradability, poor heat resistance, and the presence of toxic softeners, contributing to environmental pollution and associated detriments.[1–4]

Research studies discussed the pivotal role of food trade in global food security and emphasized the significance of transportation within food supply chains. By utilizing a global multi-region accounting framework, the carbon footprint of food-miles is estimated, revealing that transport contributes significantly to total food-system emissions. Findings suggest that global food-miles correspond to about 3.0 Gt CO_{2e}, significantly higher than previous estimates, with vegetable and fruit

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transportation contributing a substantial portion. To address environmental concerns, the text advocates for a transition towards plant-based diets and increased local production, particularly in affluent nations.[5] The escalating global burden of cancer, projected to reach 28.4 million cases by 2040, with cancer surpassing cardiovascular disease as a leading cause of death in many high-income nations. It emphasizes the role of an unhealthy diet, particularly ultra-processed foods (UPFs), as a key modifiable risk factor for cancer. UPFs, characterized by their high energy density and poor nutritional quality, have been increasingly consumed worldwide, especially in countries like the UK and US. Despite growing evidence linking UPF consumption to adverse health outcomes such as obesity and type 2 diabetes, limited research exists on their association with cancer. The study aims to comprehensively assess the relationship between UPF consumption and cancer risk in a large British cohort, considering factors such as nutritional composition and potential carcinogenic contaminants from industrial processing.[6] A rise of 10% in the consumption of ultra-processed foods was linked to a notable increase of over 10% in the likelihood of developing both overall and breast cancer. Additional research is necessary to gain deeper insights into how different aspects of food processing, including nutritional content, additives, packaging materials, and newly formed contaminants, contribute to these correlations.[7]

For more than fifty years, the global rise in wealth has consistently led to increased use of resources and emissions of pollutants at a faster rate than technological advancements have been able to reduce them. Affluent individuals worldwide bear the greatest responsibility for environmental impacts and are crucial to any efforts aimed at restoring safer environmental conditions. We provide an overview of the evidence and propose potential solutions. Achieving sustainability requires not only technological progress but also significant changes in lifestyles. However, existing societal structures, economies, and cultures promote consumption growth, while competitive market economies prioritize growth, hindering the necessary societal transformations. In understanding the true sustainability of food products, it's imperative to recognize the significance of evaluating them within the broader context of business models. Sustainability assessments must adopt a holistic perspective, taking into account the entire supply chain from production to consumption. This approach ensures that environmental, social, and economic factors are considered comprehensively. Moreover, acknowledging the risk of greenwashing, we pledge to uphold transparency in our evaluations, avoiding the promotion of unsustainable practices under the guise of sustainability. Furthermore, we are committed to addressing systemic issues within the food industry that hinder genuine sustainability efforts. By tackling these challenges head-on, we strive to foster a food system that is truly sustainable for both present and future generations.[8,9]

In the contemporary world, the discourse on sustainability has gained unprecedented momentum, extending its influence across various domains. This includes a pronounced focus on the packaging industry, a critical player in the modern consumer-driven economy. As the global community strives to minimize waste and reduce its ecological impact, a notable shift towards sustainable packaging materials has emerged. This review aims to comprehensively explore the advancements in

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this field, highlighting the progress that has steered the community toward a more environmentally conscious paradigm. A pivotal breakthrough in sustainable packaging lies in the development of biodegradable plastics, derived from renewable sources like corn starch or sugarcane. Materials such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA) have surfaced as viable alternatives, offering biodegradability without compromising on performance or functionality. Compostable packaging primarily composed of natural fibers such as paper, cardboard, or bagasse, has gained significant traction, promising to enrich the soil with valuable nutrients as it degrades. Similarly, the innovative use of mycelium, the network of fungi, has led to the creation of mushroom packaging, boasting impressive insulation and shock-absorbing properties. These nature-inspired alternatives open up exciting prospects for sustainable and organic packaging solutions. Moreover, an increased emphasis on recycling has fueled advancements in using recycled and recyclable materials, promoting a circular economy and reducing the demand for virgin resources.[8–12]

Sustainable food packaging materials we are going to discuss in this review refer to materials used in packaging production that embody the principles of sustainability, integrating economic, social, and environmental considerations throughout their life cycle, from creation to disposal, across all stages of the supply chain. By applying the concept of sustainability to packaging production, these materials aim to achieve safe, healthy, market-efficient, and cost-effective packaging solutions. Sustainable packaging is characterized by the utilization of renewable energy sources, the use of renewable or recyclable materials, and the adoption of clean production technologies and best practices. It is designed to optimize the use of materials and energy and is capable of being efficiently recovered and reused in multiple production cycles.[2]

Through an in-depth analysis of these materials, this review intends to shed light on their benefits, limitations, and transformative potential within the packaging industry. By embracing these sustainable packaging solutions, people and packaging industry can collectively work towards reducing waste generation, conserving resources, and preserving the planet earth for future generations. This exploration is enriched with valuable insights into the driving forces behind the development of smart packaging (Fig. 1),[10] along with a comparative illustration of active and intelligent packaging (Fig. 2).[10]

2. NON sustainable to sustainable food packaging. why?

2.1. Commonly used materials for food packaging

There are several types of materials commonly used in food packaging, including:[13,14]

Plastic: plastic is one of the most commonly used food packaging materials. It is lightweight, versatile, and cost-effective. However, some plastics may contain harmful chemicals that can leach into food.

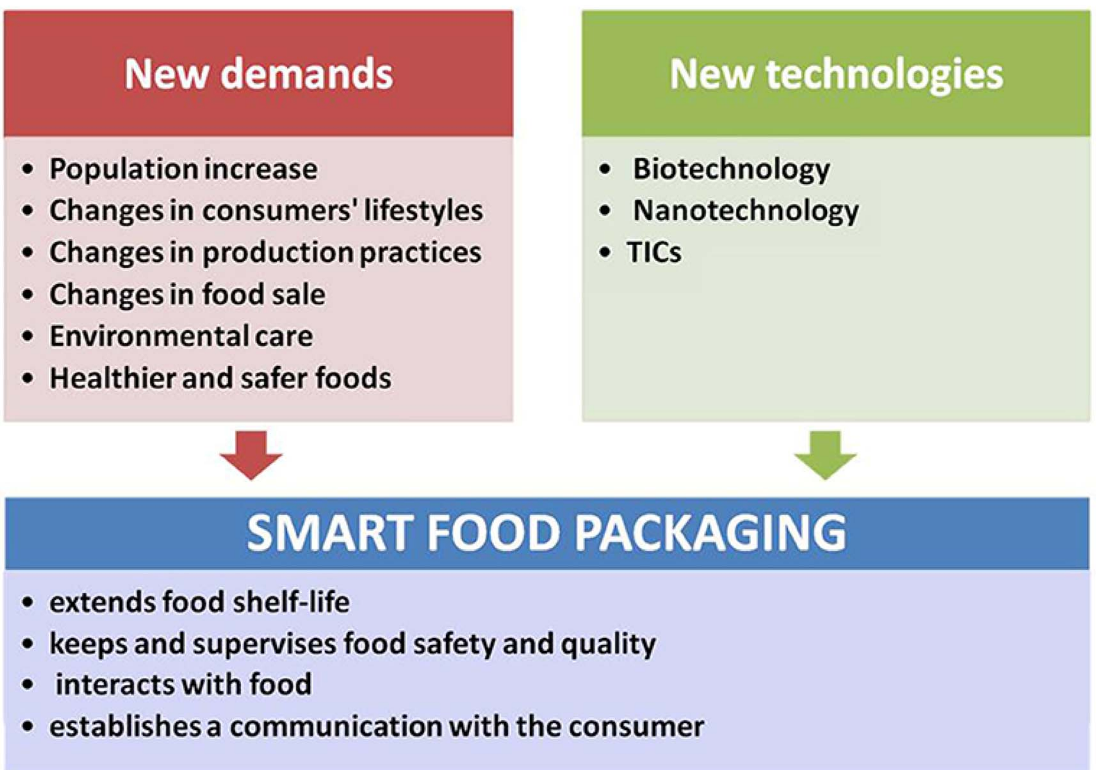

Fig. 1 Driving forces for the development of smart packaging.[10]

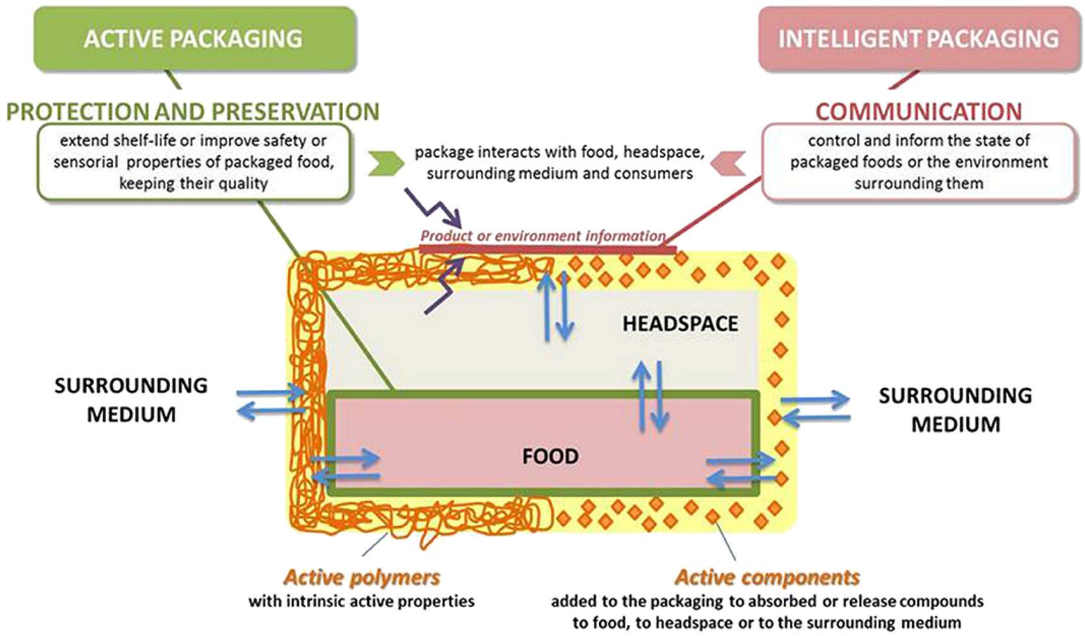

Fig. 2 Active and intelligent packaging.[10]

Glass: glass is a nonporous, inert material that is ideal for food packaging because it doesn't interact with food or alter its flavor. However, it is heavy and can be easily broken, making it less practical for some applications.

Paper and cardboard: paper and cardboard are widely used in food packaging, particularly for dry goods such as cereals and crackers. They are biodegradable and recyclable, but may not provide as much protection from moisture and air as other materials.

Metal: metal packaging, such as aluminum cans and tin cans, is commonly used for food and beverage products. It provides a strong barrier against oxygen and light, but can be heavy and may not be suitable for all applications.

Composites: composite materials, such as laminates and co extrusions, are often used in food packaging field for the combination of properties of different materials. For example, a composite material may combine the strength of plastic with the barrier properties of aluminum.

Overall, the choice of food packaging material will depend on the specific needs of the product, as well as considerations such as cost, sustainability, and regulatory requirements.[13,14] A general representation of classification of various food packaging systems is shown in Fig. 3.[15]

2.2. Negative impacts of non-sustainable food packaging materials on the environment

Non-sustainable food packaging can have significant negative impacts on the environment. Here are some examples:[16,17]

Waste generation: non-sustainable food packaging materials such as plastic, polystyrene, and aluminum can take hundreds of years to break down, contributing to the accumulation of waste in landfills and oceans. This waste can cause harm to wildlife, pollute waterways, and emit greenhouse gases.

Energy consumption: the production of non-sustainable food packaging materials requires significant amounts of energy, which can contribute to climate change. For example, the production of plastic packaging requires the extraction of fossil fuels, which are a major contributor to greenhouse gas emissions.

Water pollution: the manufacturing process for non-sustainable food packaging materials can also produce wastewater that can pollute local water sources. This can harm aquatic life and make water unsafe for human consumption.

Deforestation: the production of non-sustainable food packaging materials such as paper and cardboard can contribute to deforestation. This can have negative impacts on biodiversity, soil health, and carbon storage.

Chemical pollution: non-sustainable food packaging materials may contain harmful chemicals such as bisphenol A (BPA) or phthalates, which can leach into food and harm human health.

In nut shell, non-sustainable food packaging can have significant negative impacts on the human health and environment. It is important to develop and promote sustainable food packaging alternatives that minimize these impacts.

Hazardous chemicals: the extensive use of chemicals in various materials used for food contact in Europe, including paper wraps, plastic packaging, glass, metal containers, and bamboo kitchenware. Despite intentional chemical usage, there are also unintended chemicals present, numbering in the tens of thousands, with only a fraction studied or known. This implies that chemicals leaching from these materials could be a significant and inadequately regulated source of food contamination. While there's considerable documentation regarding chemicals of concern in paper and board food packaging, knowledge about chemicals in other plant-based

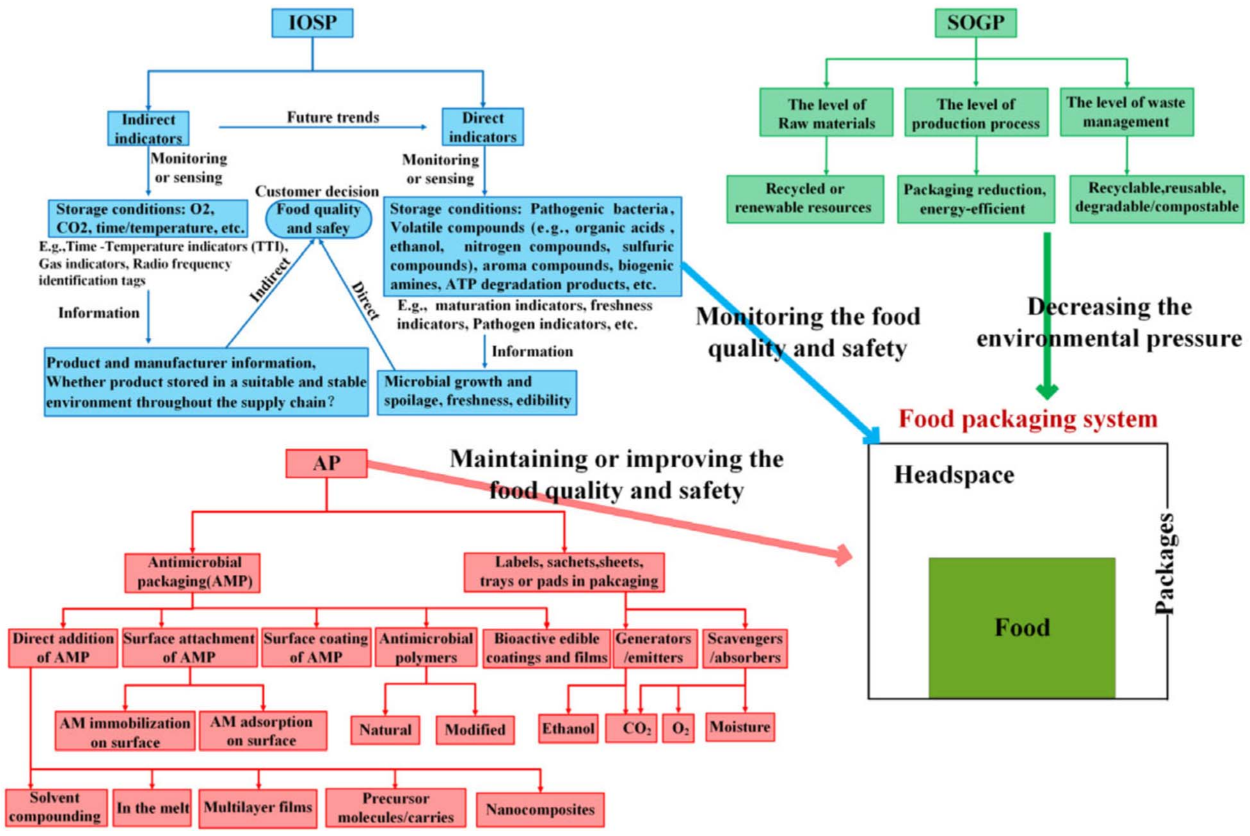

Fig. 3 Classification of food packaging systems (SOGP → sustainable or green packaging, IOSP → intelligent or smart packaging, AP → active packaging).[15] Reproduced (adapted) with permission from ref. 15. Copyright [2018] [John Wiley and Sons].

food contact materials is limited. Recent investigations have revealed troubling levels of per- and polyfluoroalkyl substances (PFAS), chloropropanols, and pesticide residues in these materials.

Per- and polyfluoroalkyl substances (PFAS) are synthetic chemicals known as 'forever' chemicals due to their persistence in the environment and tendency to accumulate in food chains. Exposure to PFAS has been associated with severe health effects such as cancer, developmental toxicity, and immunotoxicity. These chemicals are commonly used to impart water, grease, and stain resistance to food packaging, clothing, and various consumer products. PFAS can enter paper and plant-based materials intentionally through additives or coatings, or unintentionally as residues from precursor compounds or background contamination. Migration of PFAS from grease-resistant paper packaging into food is well-documented. Concerns about the impact of PFAS on human health and the environment are growing globally. The EU's recent Chemicals Strategy for Sustainability aims to ban all non-essential uses of PFAS and reduce exposure from food, water, air, and other sources. Denmark has already implemented a ban on the intentional use of PFAS in paper and fibrous materials for food contact, unless a functional barrier preventing migration into food is employed.

Chloropropanols, including 3-monochloropropane-1,2-diol (3-MCPD) and 1,3-dichloropropan-2-ol (1,3-DCP), are a group of chemical pollutants known for their carcinogenic properties. These compounds have been detected in various processed foods and food ingredients such as hydrolyzed vegetable protein, soy sauce, cereals, and smoked foods. Additionally, chloropropanols can be generated as process contaminants during the production of paper and board. For instance, paper made with wet-strength resins containing epichlorohydrin may contain 3-MCPD and 1,3-DCP. Previous studies have identified these contaminants in products like paper straws, but their prevalence in other fibrous materials like bagasse is not well-documented.

Pesticide residues can be found in plant-based food contact items either as remnants from pesticides used during the cultivation of natural materials like sugarcane and palm trees, or from treatments applied during subsequent processing, such as anti-fungal treatments. These pesticides, including herbicides, fungicides, insecticides, and others, are used to protect crops but can also harm biodiversity and pose health risks such as cancer, birth defects, and neurological issues. Despite the EU's stringent regulations on pesticide use in food and establishment of maximum residue levels, there's no explicit regulation on their presence in food packaging materials. In a study by Öko-Test in June 2018, it was found that disposable tableware made from palm tree leaves contained traces of the banned pesticide DDT alongside biological contaminants.[18]

2.3. Need and applications of sustainable and eco-friendly food packaging materials

There is a growing need for sustainable packaging materials in the modern era due to several reasons. Firstly, traditional packaging materials such as plastic, which are widely used, have negative impacts on the environment. Plastic takes hundreds of years to decompose, and it pollutes the land and oceans, harming wildlife and ecosystems. Moreover, the extraction of raw materials and the manufacturing processes required to produce traditional packaging materials contribute to greenhouse gas emissions, which worsen climate change. In response to these challenges, sustainable packaging materials are becoming increasingly important. These materials are designed to be environmentally friendly throughout their life cycle, from production to disposal. Sustainable packaging materials can be made from renewable resources, such as plant-based materials, or they can be recyclable, compostable, or biodegradable. They help to reduce waste, conserve resources, and reduce greenhouse gas emissions. The demand for sustainable packaging is growing due to increasing public awareness of environmental issues, regulatory pressure, and the need for businesses to meet sustainability goals. Sustainable packaging also provides opportunities for businesses to differentiate themselves and appeal to consumers who are increasingly eco-conscious.

Food packaging materials serve several purposes beyond just protecting the food product during transportation and storage. Some common applications of food packaging materials include:[11,12]

Preservation: packaging materials such as vacuum-sealed bags, airtight containers, and metal cans help preserve food products by preventing oxidation, moisture loss, and contamination by microorganisms.

Convenience: packaging materials such as single-serving packages, resalable bags, and easy-open lids make it easy for consumers to handle and use food products.

Branding and marketing: packaging materials with attractive designs and logos help promote brand recognition and influence consumer purchasing decisions.

Information and labeling: packaging materials can also provide important information such as nutritional information, ingredients, and expiration dates, which can help consumers, make informed choices.

Safety and security: packaging materials can protect food products from physical damage during transportation and storage, and tamper-evident packaging can help prevent food tampering and contamination.

Sustainability: packaging materials can be made from renewable or recyclable materials, reducing the environmental impact of packaging waste.

Extended shelf life: modified atmosphere packaging (MAP) and active packaging can extend the shelf life of perishable food products by controlling the atmosphere inside the package and inhibiting the growth of microorganisms.

Overall, food packaging materials play a crucial role in ensuring the safety, quality, and convenience of food products for consumers.[19,20]

The various properties of materials which make them suitable for food packaging applications are represented in Fig. 4.[21] Herein, water barrier refers to water vapor barrier of cellulose based food packaging using double layer coatings and cellulose nanofibers. Water barriers in food packaging are crucial for preserving product quality and extending shelf life by preventing moisture from entering or leaving the package. Common materials include plastic films like polyethylene and polypropylene, aluminum foil, wax-coated and plastic-coated papers, and biodegradable options like PLA. Advanced solutions include multilayer laminates, active packaging with moisture absorbers, and innovative coatings such as silicon oxide and nanocomposites. These barriers are essential for maintaining the freshness, safety, and nutritional value of food products, reducing spoilage and waste throughout the supply chain.[22]

2.4. Need for sustainability in food packaging materials

There is a growing need for sustainability in food packaging for several reasons:[23]

Environmental impact: traditional food packaging, such as plastic, often ends up in landfills or pollutes the environment, causing harm to wildlife and ecosystems.

Resource depletion: many traditional materials for food packaging are made from non-renewable resources, such as petroleum, which are becoming increasingly scarce and expensive.

Consumer demand: consumers are becoming more aware of the impact of their purchasing decisions on the environment, and are demanding more sustainable options.

Regulatory requirements: Governments around the world are implementing regulations to reduce waste and promote sustainability, which includes food packaging.

To address these challenges, the food industry is increasingly turning to more sustainable packaging solutions, such as biodegradable, compostable, and recyclable materials. By using sustainable packaging, the food industry can reduce waste, conserve resources, and meet the growing demand for environmentally responsible products.[23]

2.5. A brief timeline of food packaging materials

Here is a brief timeline of food packaging materials:[24]

➢ Early history: people used natural materials such as leaves, animal skins, and woven baskets to store and transport food.

➢ 1800s: paper and glass began to be used for food packaging.

➢ Early 1900s: tin cans were invented, making it easier to transport and store food.

➢ Mid-1900s: plastic packaging became more popular due to its versatility and cost-effectiveness.

➢ 1960s: the first recyclable plastic, polyethylene terephthalate (PET), was invented.

➢ 1970s: concerns about the environmental impact of packaging led to the development of biodegradable materials.

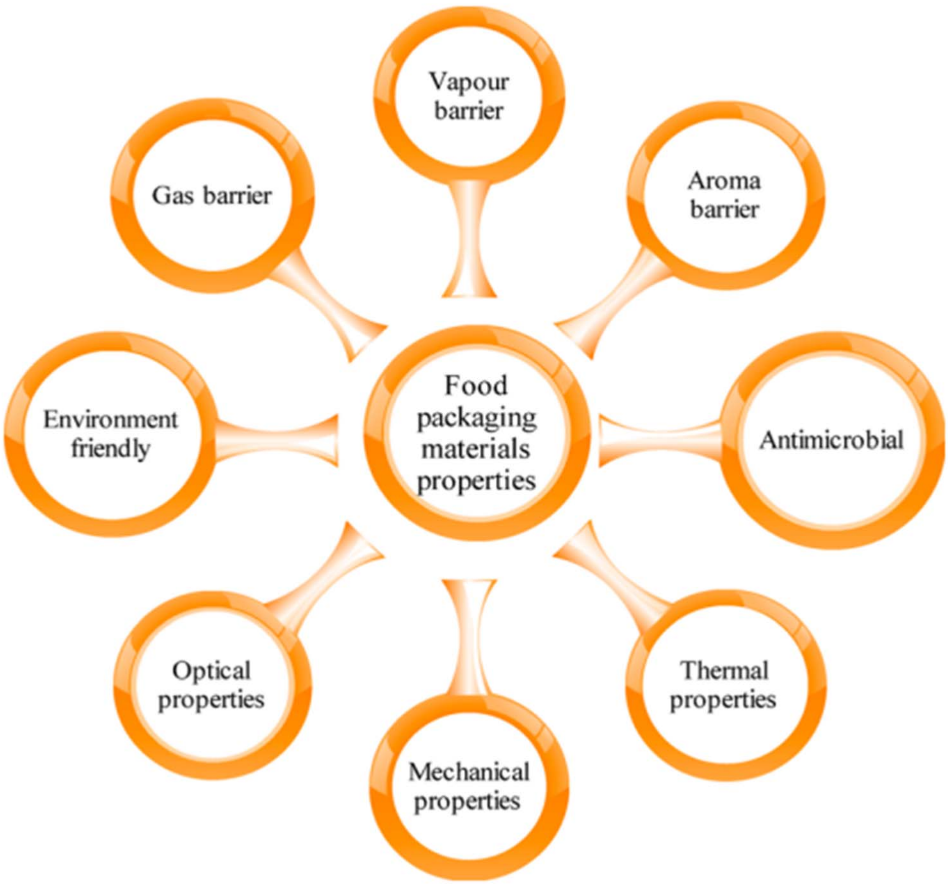

Fig. 4 Quality determining properties of food packaging materials.[21] Reproduced (adapted) with permission from ref. 21. Copyright [2018] [ACS].

➢ 1990s: compostable packaging materials were introduced, made from renewable resources like cornstarch and sugarcane.

➢ 2000s: innovations in packaging included the active and intelligent packaging development, which can help preserve food freshness and safety.

➢ 2010s: the use of sustainable materials like bamboo, mushroom, and seaweed for food packaging gained popularity.

➢ Nowadays: today, there is a growing trend towards the use of more sustainable packaging solutions, such as biodegradable, compostable, and recyclable materials, as the food industry aims to reduce waste and promote sustainability.

2.6. General examples of sustainable food packaging materials

To address these challenges, the food industry is increasingly turning to more sustainable packaging solutions, such as biodegradable, compostable, and recyclable materials. Some examples of sustainable food packaging materials include:[25]

Bioplastics: these are plastics made from renewable resources like corn, sugarcane, and potatoes, which can biodegrade in the environment.

Paper-based materials: these are made from sustainable materials like bamboo, wheat straw, and recycled paper.

Plant-based materials: these are made from natural materials like seaweed, mushroom, and sugarcane waste.

Compostable materials: these are designed to break down in a composting environment, leaving no harmful residue.

By using sustainable packaging, the food industry can reduce waste, conserve resources, and meet the growing demand for environmentally responsible products.

Table 1 represents some important food packaging materials & their functionalities.

3. Advanced food packaging materials and methods

3.1. Polymer packaging materials

Polymer packaging materials are of four important types as shown in Fig. 5.[33]

Bioplastics serve as a preferable substitute for petrochemical-based plastics due to the increased harmful impacts associated with the latter (Fig. 6).[34] The benefits of bioplastics, such as a reduced carbon footprint, support for rural economies, and use of renewable resources, confer it with distinct advantages. Conversely, the non-biodegradable nature, limited renewability, and adverse health implications stemming from the emission of hazardous gases, among other characteristics, render petrochemical-based plastics less desirable.

Table 1 Important food packaging materials and their functionalities

Packaging material	Functionality	References
Poly glycolic acid (PGA)	Barrier property	26
Nanofiller blended biopolymer	Barrier property and hydrophobicity	27
Plastic films	Printability, barrier property and sealing	28
Cellophane	Excellent elasticity and mechanical property	29
PLA reinforced with cellulose nanowhiskers	Water vapor and oxygen barrier properties	30
Chitosan reinforced with bacterial cellulose micro- and nanofibers	Bactericidal, mechanical, water vapor barrier and bacteriostatic	30
Paper	Printability	31
Paper processed in biopolymer coating	Good barrier property	32
Paper sheet containing polyaniline (PANI) and polystyrene (PS), in the presence of dispersed bagasse pulp fibers	Antibacterial property	29
Inorganic nanoparticle	Antimicrobial	29
Organic nanoparticle	Good tensile strength, mechanical property, environmental friendly, barrier property and reduced cost	29
Bio nanocomposite	Good mechanical, heat resistance property and barrier property	29

Bioplastics are presented as a greener option to traditional petroleum-based plastics. Despite their low market share, expected growth suggests increasing popularity. The term encompasses materials made from renewable sources, those designed to degrade naturally, or both. However, it's unclear if plant-based blends qualify. Bioplastics are marketed as sustainable, but scientific support for their environmental benefits is limited. Some biodegradable plastics do not degrade effectively in natural environments because they require specific conditions, such as high temperatures and controlled microbial activity, which are not typically present outside industrial composting facilities. As a result, they may persist longer than expected, fragment into microplastics, or leave toxic residues. Assessment often focuses on production and end-of-life aspects, neglecting chemical safety during use. Understanding chemical composition and toxicity is crucial as human exposure will rise with increased usage. Plastics contain various intentionally added compounds like plasticizers and stabilizers, alongside unintentional substances. These chemicals can migrate into the environment, posing risks to humans and ecosystems.[35]

3.1.1. Petroleum based packaging materials. Petroleum-derived polymers hold a significant and predominant role in the domain of food packaging, thus experiencing widespread

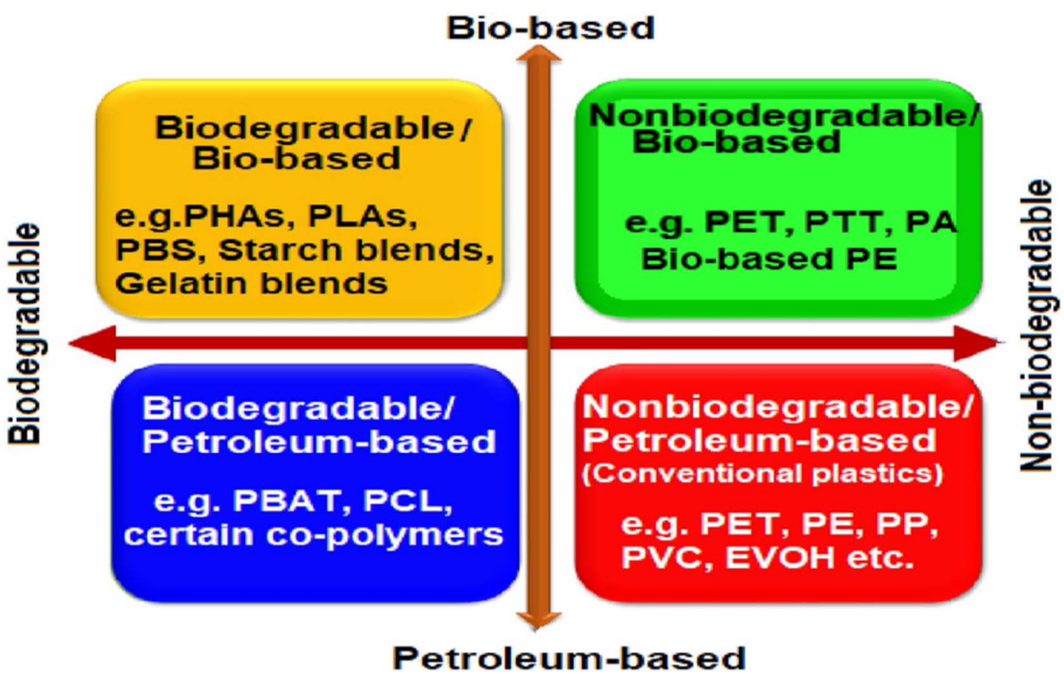

Fig. 5 Different types of polymer packaging materials.[33] Reproduced (adapted) with permission from ref. 33. Copyright [2020] [Elsevier].

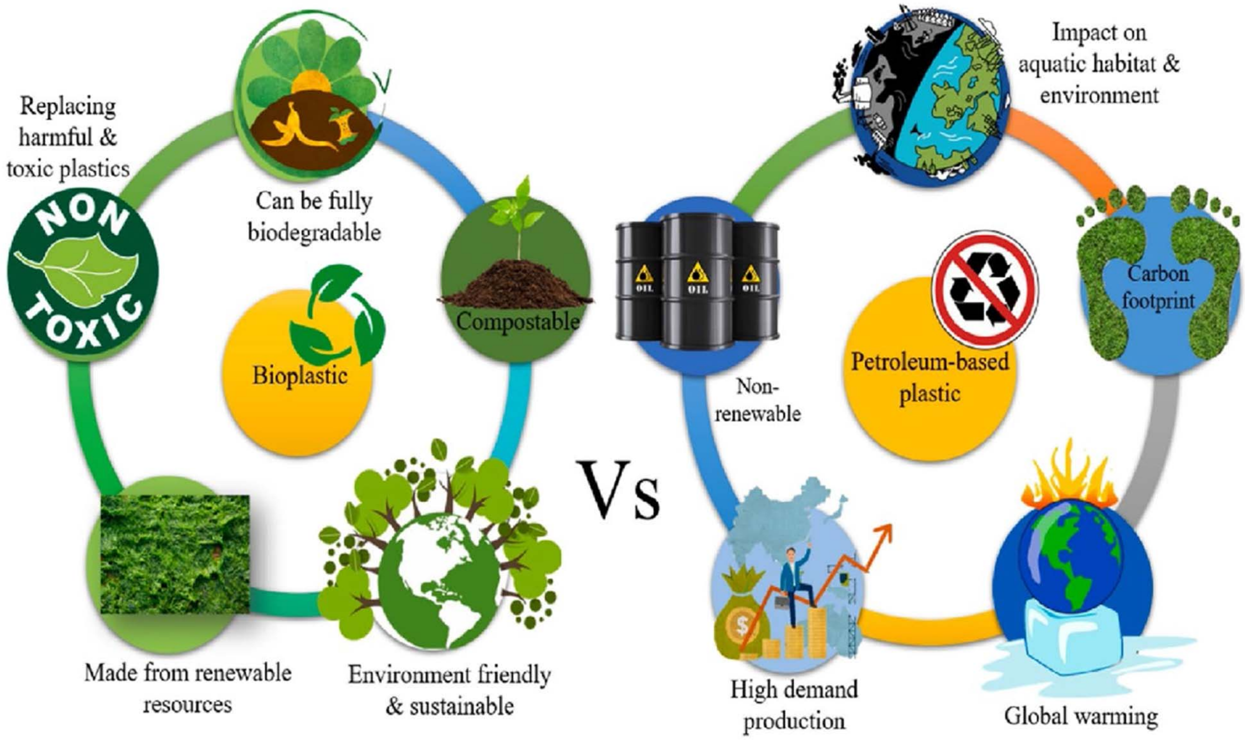

Fig. 6 Comparison between bioplastic and petroleum-based plastics.[34] Reproduced (adapted) with permission from ref. 34. Copyright [2022] [Elsevier].

usage in this sector. Alongside favorable attributes including ease of processing and excellent mechanical and barrier properties, the major detrimental concerns of these polymers lie in their lack of degradability and the emission of greenhouse gases.[36] Among the commonly utilized petroleum-based polymers in food packaging are polypropylene (PP), poly (vinyl chloride) (PVC), polyethylene (PE), polyamides (PA), polyurethane (PU), expanded polystyrene, polystyrene (PS), and poly (ethylene terephthalate) (PET).[37]

3.1.2. Bio-based packaging materials. These polymers originate from living organisms, including plants and microbes, and are created through metabolic engineering processes and renewable resources, such as food waste, wood, agricultural waste, polysaccharides, or lignocelluloses[38] (Fig. 7).[39]

Biodegradability, biocompatibility, and other similar characteristics of such polymers make them ideal for food contacts. Biobased polymers are divided into three groups on the basis of methods of synthesis: microbially originated polymers, protein based polymers and wood based polymers.

Table 2 represents the active/intelligent agent blended biobased materials.[39]

3.1.2.1. Microbially originated polymers. This category of polymers can be produced through the utilization of a fermentation process. Enzymatic catalysts facilitate the fermentation process, utilizing various renewable feedstocks as substrates.[48] Microorganisms are capable of biosynthesizing a range of biopolymers, including but not limited to polyhydroxyalkanoates, xanthan, polysaccharides, dextrans, oligosaccharides, pullulan, organic acids, glucans, cellulose, gellan, hyaluronic acid, alginate, levan, cyanophycin, and poly (gamma-glutamic acid).[49] Below, there is discussion of some significant polymers derived from microorganisms.

3.1.2.1.1 Polyhydroxyalkanoates (PHA). PHA was initially discovered by Beijernick and his associates, and it is manufactured through bacterial cell fermentation. Among the various categories of PHA, including polyhydroxybutyrate, polyhydroxyvalerate, polyhydroxyhexanoate, and polyhydroxyoctanoate, PHB stands out as the most preferred option due to its widespread acceptance and durability, closely resembling conventional plastics.[50] The Gram-negative bacterium *Alcaligenes eutrophus* synthesizes PHB as an energy reserve in the presence of a high carbon supply, with limited quantities of phosphorus, oxygen, nitrogen, and sulfur. This process accounts for approximately 70 to 80% of the bacterial cell's dry weight, depending on the microbial colony and the carbon source.[51] Various renewable resources, including waste materials from food such as domestic waste, maltose, fats, xylose, frying oil, starch, crude glycerol, fructose, as well as gases and *n*-alcohol, serve as viable sources for PHA synthesis.

The formation of PHA polymers involves the linking of several monomers, resulting in unique properties such as biodegradability and characteristics similar to those of conventional plastics.[52] Owing to its high biodegradability and other similar attributes, PHA is particularly well-suited for use in short-term packaging applications.

Fig. 7 Substrate sources for biopolymer production.[39] Reproduced (adapted) with permission from ref. 39. Copyright [2022] [Springer Nature].

3.1.2.1.2 Polylactic acid. PLAs can be produced from aliphatic monomers, such as lactic acid, either through chemical synthesis or starch fermentation. The fermentation process can utilize various carbohydrate-rich sources like kitchen waste, wheat, sugarcane, or corn. The synthesis of PLA involves several key steps, including lactic acid production, the formation of lactide monomers, and subsequent polymerization.[53] PLA's popularity in food packaging can be attributed to its non-toxic nature, optimal mechanical strength, renewability, and biodegradability. Additionally, its production emits fewer carbon emissions, consumes less energy, and generates minimal waste. Despite its limitations in heat resistance, ongoing research efforts over the past decades have focused on enhancing its properties and reducing costs. Blending PLA with cellulose has been explored as a strategy to improve its heat resistance.[54] Furthermore, the incorporation of various fillers and polymers has been investigated to enhance the performance of the final product while minimizing costs. Additionally, the addition of nanofillers, such as silica and talc, and nanoadditives can lead to further improvements in PLA's physical and chemical properties.

Table 2 Active/intelligent agent blended biobased materials

Biobased nanomaterials	Active/intelligent agent	References
Nanocellulose	Flavonoid silymarin	40
Nanocellulose	Ferulic acid & derivatives	41
Bacterial nanocellulose	Sulfobetaine methacrylate	42
Nanofibrillated cellulose (NFC)	Tannins	43
Cellulose nanocrystal (CNC)	Wheat gluten incorporating TiO_2 nanoparticles	44
AgNP/BNC-PVA	Ag NPs	45
Bacterial nanocellulose	Methyl red	46
Sugarcane bagasse nanocellulose hydrogel	Zn^{2+} cross-linking	47

Recent investigations have demonstrated that PLA possesses antimicrobial activity. Surface coatings of PLA integrated with substances like silver nanoparticles, cellulose nanocrystals, sophorolipid, and lysozyme exhibit preventive effects against microorganisms such as *Staphylococcus aureus*, *Escherichia coli*, *Listeria monocytogenes*, *Salmonella* spp, and *Micrococcus lysodeikticus*. These coatings have also demonstrated the potential to extend the shelf life of perishable fruits.[55]

3.1.2.1.3 Exopolysaccharides. These long-chain polysaccharides can be generated through the bacterial fermentation of various sources, including dairy waste, carbohydrate-rich food waste, sugarcane juice, potato peel, coconut waste, and sugarcane molasses. While lactic acid bacteria (LAB) have historically been employed for enhancing the functional properties of food in terms of prebiotics and probiotics, their role has expanded significantly with the growing emphasis on safe food consumption and technological advancements. LAB are now extensively utilized for the production of exopolysaccharides, contributing to improvements in food texture and secure packaging. In addition to Gram-negative and Gram-positive bacteria, exopolysaccharides can also be synthesized by fungi, yeast, and blue–green algae.[56]

Exopolysaccharides produced by LAB are instrumental in formulating edible coatings or films for food products, owing to their favorable structural integrity, as well as their smooth and lustrous surface. Integrating exopolymers with other nanocomposites not only enhances productivity from LAB but also imparts antioxidant and antimicrobial properties.[57] The preparation of composite EPS films achieved through the incorporation of sodium carboxymethylcellulose (CMC) with lactic acid bacteria (*Lactobacillus plantarum*), results in films with reduced moisture absorption capacity and improved antioxidant activity.[58,59] Kafiran, distinguished by its biodegradability and antimicrobial properties, is gaining notable attention within the spectrum of exopolysaccharides.

3.1.2.2. Wood based polymers. Lignocellulosic polysaccharides serve as the primary source for the production of these polymers, comprising approximately 40 to 50% cellulose, 20 to 30% hemicellulose, and 20 to 25% lignin (Fig. 8).[60] Wood fibers have diversified applications not only in wood products but also in non-wood products, assorted panel boards, and paper products.[60]

Some important wood based polymers are discussed below.

3.1.2.2.1 Cellulose & hemicellulose. To harness the multifaceted attributes of cellulose, such as its capacity to augment color, enhance mechanical properties, bolster barrier properties, and improve dyeing, various materials can be introduced alongside cellulose nanoparticles.[60] The combination of chitin with cellulose nanocrystals yields a homogenous surface, establishes a robust percolating network, and serves as fillers to achieve optimal tensile strength.[61] When nanocellulose and alginate polymers form nanocomposite films, the resultant product exhibits commendable tensile strength, although increasing the concentration of cellulose nanomaterials renders the film transparent.[62]

For the development of biodegradable films with low water vapor permeability, carboxymethyl cellulose (CMC) extracted from sugarcane bagasse can be amalgamated with gelatin, glycerol, and agar.[63] Fig. 9 (ref. 39) illustrates the progression of the development of CMC-blended bioplastics.

Cellulose monomers play an important role in the production of polymer as represented in Fig. 10.[64]

Hemicellulose is regarded as one of the potentially more environmentally friendly alternatives to plastics for food packaging. Methods such as hot water extraction, alkali extraction, acid extraction, and steam explosion are commonly employed for the extraction of hemicellulose from plant cells. Notably, the

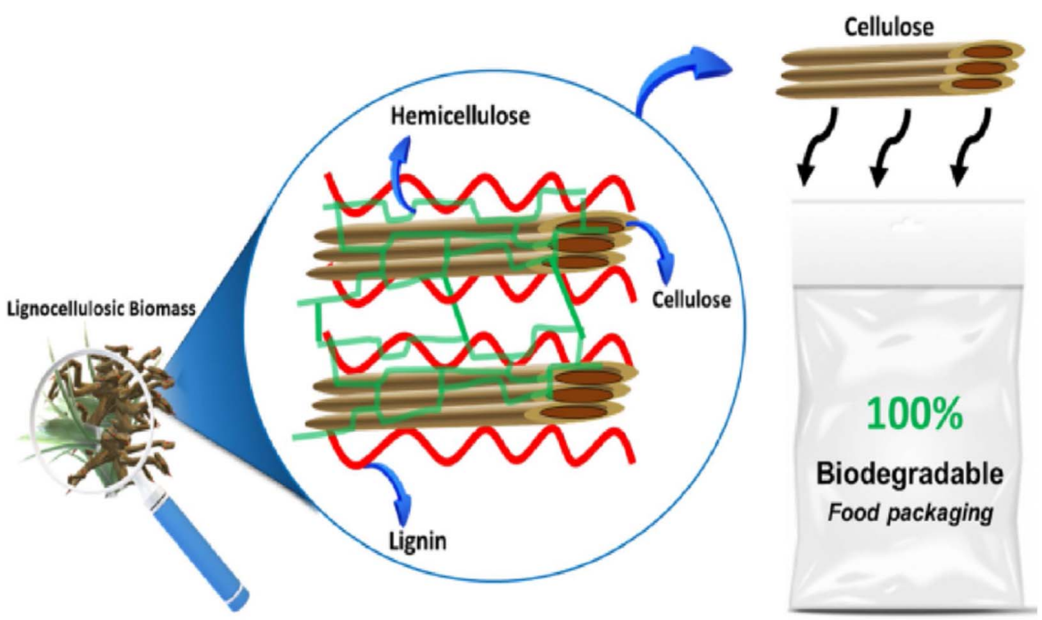

Fig. 8 Lignocelluloses biomass-composition.[60]

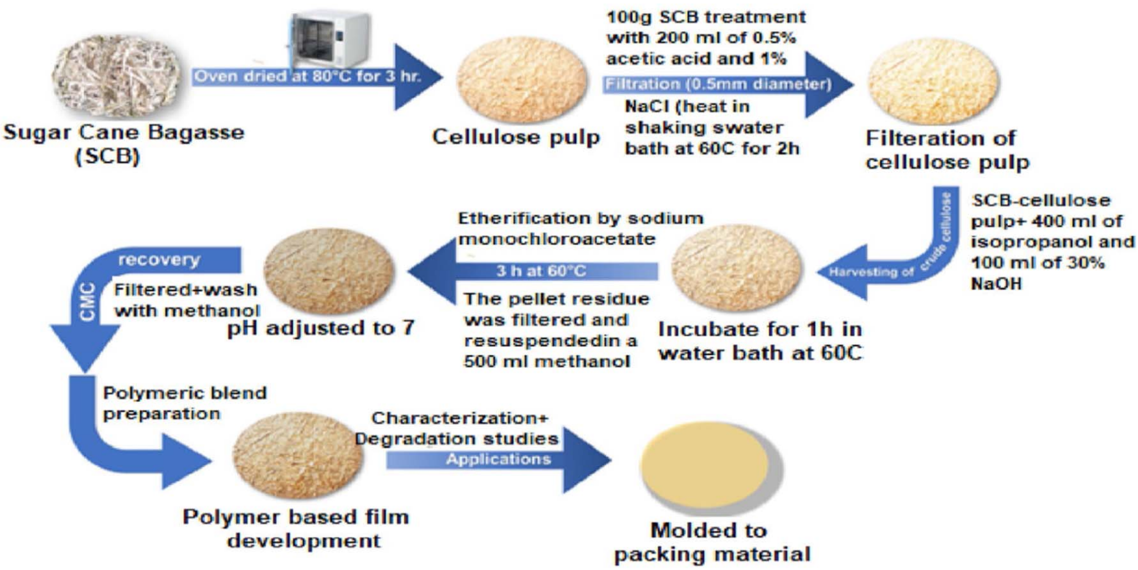

Fig. 9 Flow of development of CMC bioplastics.[39] Reproduced (adapted) with permission from ref. 39. Copyright [2022] [Springer Nature].

two-step alkali extraction-delignification method yields the highest output at 84%. With its low molecular weight and hydroxyl functional group, hemicellulose can be utilized in film production using the casting and drying method, making it suitable for food packaging.[65] Fig. 11 (ref. 39) illustrates the process of film formation from hemicellulose solution.

3.1.2.2.2 Chitosan/chitin. Because of the existence of amino and hydroxyl groups on chitosan, it exhibits antimicrobial properties against a range of bacterial species, including both Gram-negative and Gram-positive types. Films derived from the combination of chitosan with diverse materials demonstrate outstanding antioxidant and antimicrobial activities suitable for food packaging.[66,67] The distinctive properties of chitosan enable its application in the production of food packaging films and coatings.

3.1.2.2.3 Lignins. Roughly eighty million tons of the available lignin are annually consumed in the paper-making industry, with only 2% utilized in processing and the remaining 98% wasted as fuel. Up to 90% of the technical lignin produced comes from kraft lignin and lignosulfonates, acquired through the delignification method.[68] The hydrophilic nature and the presence of hydroxyl groups on lignin polymers facilitate its incorporation with polylactic acids, starch, and amino acids, enhancing mechanical properties and reducing moisture absorption characteristics. When used as a reinforcing material blended with starch extracted from sago palm, lignin contributes to improved barrier properties and seal

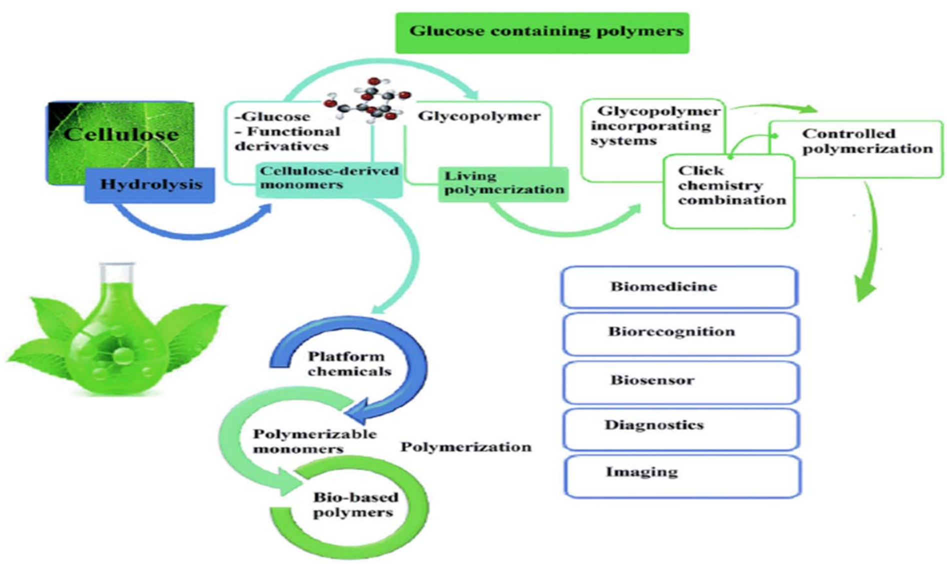

Fig. 10 Possible applications of cellulose monomers for polymer production.[64] Reproduced (adapted) with permission from ref. 64. Copyright [2018] [RSC].

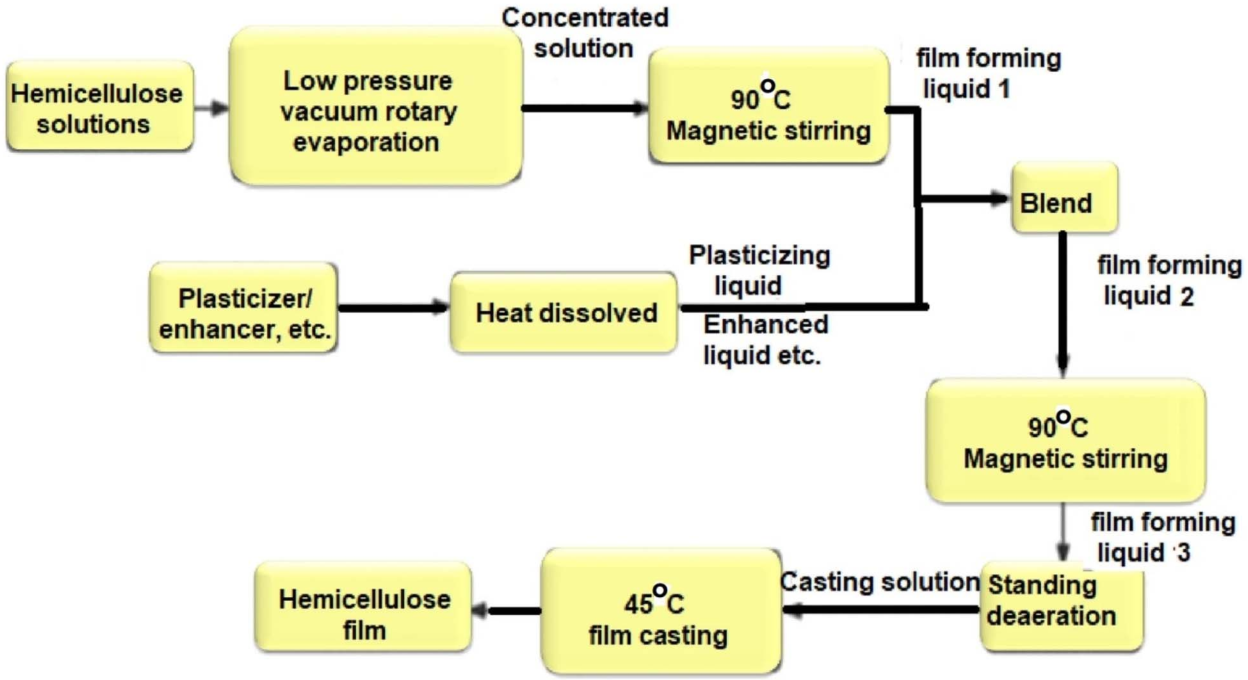

Fig. 11 Flow chart of hemicellulose film formation.[39] Reproduced (adapted) with permission from ref. 39. Copyright [2022] [Springer Nature].

strength in packaging films.[69] Additionally, lignin can function as a stabilizer and plasticizer alongside PLA, cellulose, and PLB polymers, promoting the production of biocompatible and biodegradable bioplastics.[70]

3.1.2.3. Protein based polymers

3.1.2.3.1 Gelatin & collagen. Gelatin is derived from the partial hydrolysis of collagen, resulting in an odorless protein characterized by a random polypeptide chain. Its exceptional functional properties render it a valuable biopolymer within the food packaging industry. The two primary types of gelatin, type A and type B, are distinguished by their processing methods. Type A gelatin, with an isoelectric point between pH 8 to 9, is acquired through collagen treatment with acids. Conversely, type B gelatin, with an isoelectric point between pH 4 to 5, is obtained by collagen treatment with alkali, leading to the conversion of asparagine and glutamine residues into their acids, thereby achieving higher viscosity. Type A gelatin is sourced from pig skin, while type B gelatin is sourced from bones and beef skin.[69]

Films produced from gelatin tend to exhibit high moisture absorption, necessitating various enhancements to modify its hydrophilic nature. Crosslinking modifications, facilitated by the addition of natural extracts, have been shown to enhance gel strength in comparison to pure gelatin film.[70] The antimicrobial and antioxidant properties of gelatin can be amplified by blending it with other materials, including zinc oxide nanoparticles, chitosan, and tea polyphenols, among others.[71]

3.1.2.3.2 Soy protein. The soy-based film, renowned for its desirable properties in food packaging applications, boasts exceptional texture-forming capabilities, strong adhesiveness, and effective fiber binding. These films are derived from soy protein isolates, which contain approximately 90% protein content.[72] Soy protein isolates can be precipitated from diverse soy sources, including crude soybean, soy milk, or soy flour. Various sources of soy yield soy-based films with distinct functional and mechanical properties, as well as different molecular weights. Incorporating different substances into soy-based films can contribute to enhancing their physical and mechanical characteristics.[73] For instance, the addition of stearic acid and cysteine leads to improvements in several properties of soy-based films, such as reduced water vapor permeability and water absorption capacity, along with enhanced tensile strength.[74] Beyond soy proteins, pea proteins, zein proteins, and globulin proteins are also viable options for food packaging applications.[74]

3.1.2.3.3 Casein & whey proteins. Both casein and whey proteins are derived from milk subsequent to cheese production. Owing to intermolecular hydrogen and electrostatic bonds, casein can be employed to create films within aqueous solutions. However, the hydrophilic nature of these films renders them susceptible to moisture. By introducing polysaccharides, genipin, lipids, wax, and glutaraldehyde *via* crosslinking, the chemical and physical properties of these films can be significantly enhanced, resulting in reduced moisture absorption capacity and prolonged shelf life.[75] Whey protein concentrates and whey protein isolates, both rich sources of sulfur-containing amino acids such as cysteine and methionine, are utilized in the production of whey-based food packaging. Plasticized whey-based films can be developed by heating the whey protein isolate solution for denaturation over a few minutes at temperatures ranging from 80 to 100 °C. A more uniform WPC film can be achieved by treating the solution at 75 °C for 30 minutes under an alkaline pH of 6.6. Furthermore, exposing the film to UV treatment within an alkaline pH range of 7 to 9 can enhance uniformity, tensile strength, and elasticity. The addition of lipids, such as fatty acids, waxes, or plant oils, serves to mitigate the hydrophilic nature of the film.[76]

Petroleum-based packaging materials have been the backbone of the packaging industry due to their durability and cost-effectiveness. However, their widespread use contributes to plastic pollution, resource depletion, and the persistence of non-biodegradable waste. As environmental concerns mount, the shift towards bio-based packaging materials has gained momentum. Bio-based packaging materials are derived from renewable sources such as plants and agricultural waste. They offer a more sustainable alternative by reducing the reliance on fossil fuels and decreasing carbon emissions during production. These materials can also be engineered for biodegradability or compostability, addressing the problem of packaging waste that lingers in the environment. Polylactic acid (PLA) is a prime example of a bio-based material. Derived from corn starch, PLA offers transparency and moderate barrier properties. It can be used in various applications, from food containers to beverage cups. Polyhydroxyalkanoates (PHA) are another promising bio-based option. Produced by microorganisms, PHA is biodegradable and exhibits diverse mechanical properties. These materials have the potential to revolutionize the packaging landscape by offering both functionality and sustainability.

3.2. Bio-nanocomposites in food packaging

3.2.1. Biopolymers. Biopolymers, commonly referred to as biodegradable plastics, are polymeric materials that undergo the metabolism of naturally occurring organisms as part of their degradation process.[77,78] However, their utilization in the industrial sector is limited due to their inadequate mechanical and barrier properties. The challenges of performance, processing, and cost are common issues associated with biopolymers regardless of their origin.[79–81] In addition to these factors, various limitations further restrict their applications, such as low heat distortion temperature, brittleness, high gas and vapor

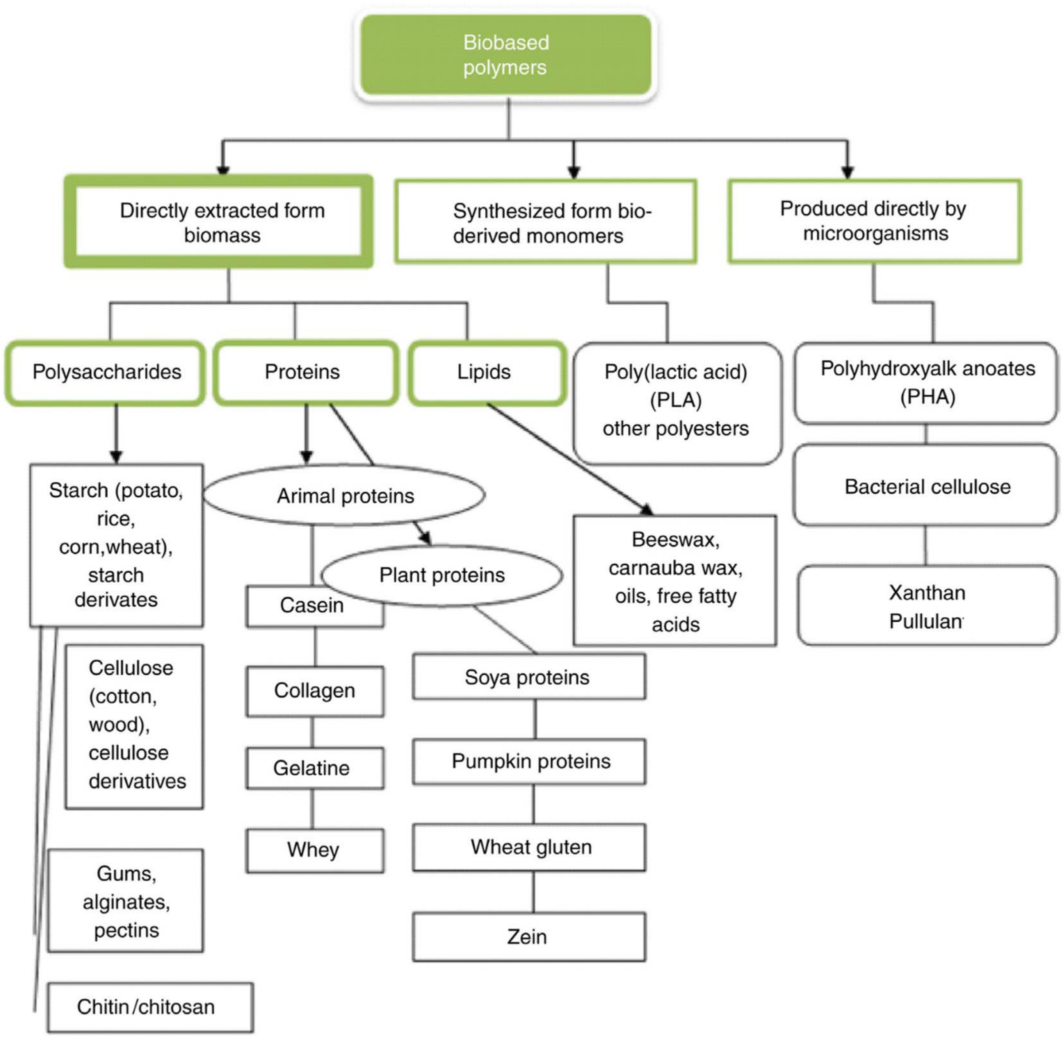

Fig. 12 Classification of biopolymers.[87] Reproduced (adapted) with permission from ref. 87. Copyright [2018] [Elsevier].

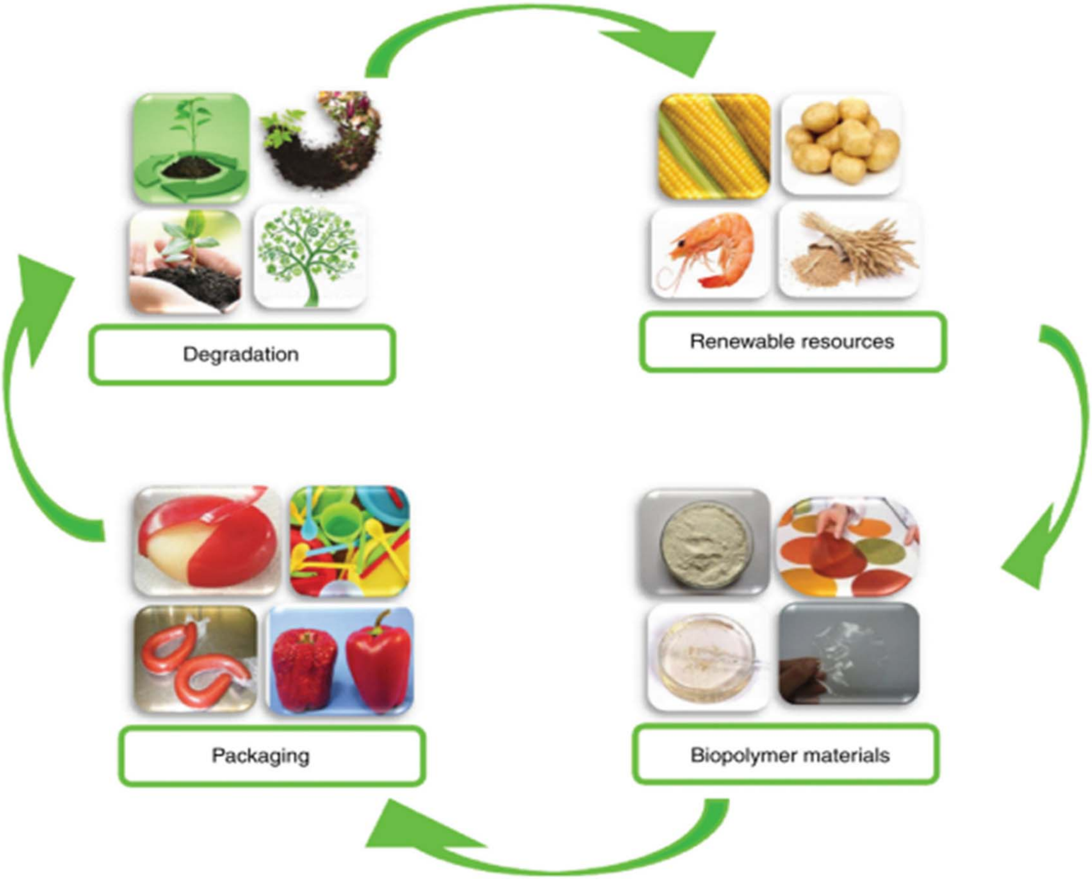

Fig. 13 Life cycle of biopolymer packaging materials.[87] Reproduced (adapted) with permission from ref. 87. Copyright [2018] [Elsevier].

permeability, and poor resistance to prolonged processing.[82–86] Despite these constraints, they find application in food packaging materials due to unique packaging-related enhancements. Fig. 12 (ref. 87) provides a schematic representation of the classification of biopolymers, while Fig. 13 (ref. 87) illustrates the life cycle of biopolymer packaging materials.

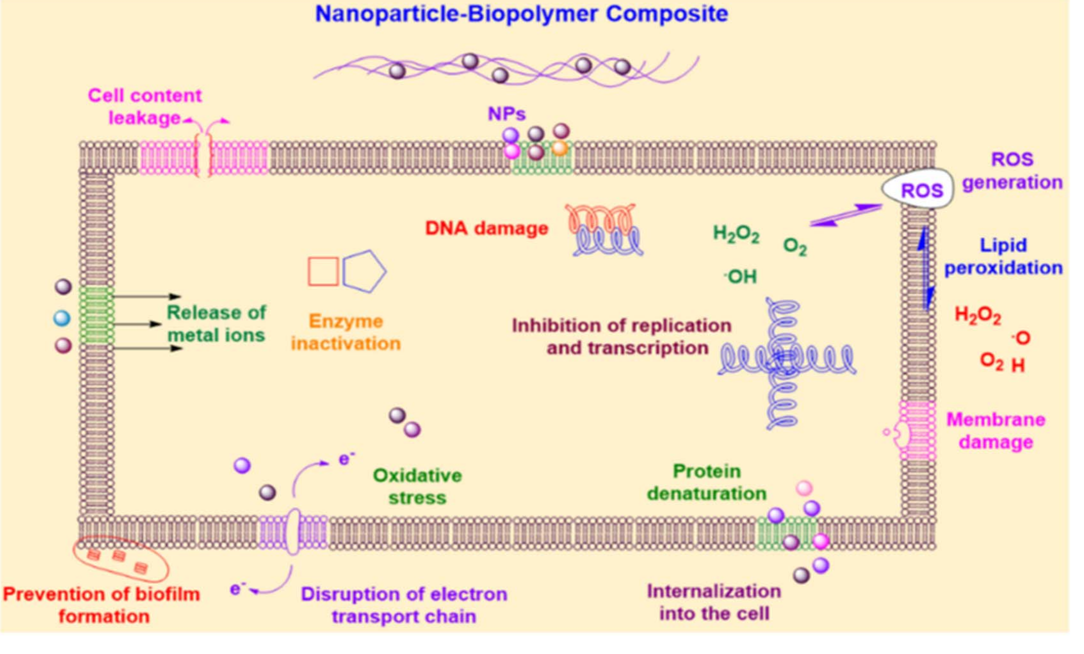

Fig. 14 Antimicrobial mechanisms of action of nanocomposites designed for food packaging.[96]

3.2.2. Biopolymer-based nanocomposites. Nanocomposite technology stands out as one of the pivotal technologies that effectively addresses the inherent limitations of biopolymer-based packaging materials.[88] When compared to neat polymers and their conventional composites, nanocomposites demonstrate improved properties, including enhanced mechanical strength, superior barrier properties, and improved heat resistance.[89–92] For instance, the incorporation of montmorillonite clay in nylon enhances its mechanical and thermal properties.[93] Utilizing such nanocomposites in food packaging applications result in advancements in food technology processes, allowing for better endurance during thermal processing, storage, and transportation.[90,94] The preparation and characterization of various types of biodegradable polymer nanocomposites constitute an area of significant research importance, with numerous research groups actively engaged in this field. These biodegradable polymer nanocomposites, known as bio-nanocomposites, exhibit various unique properties that cater to a wide range of applications.[95] The presence of layered silicates within plays a crucial role in enhancing the desirable properties of both natural and synthetic biodegradable polymers, while preserving their biodegradability. The inclusion of clay layers in these polymers significantly bolsters their barrier properties by obstructing the molecular pathway, resulting in a more convoluted diffusive path.[87] Fig. 14 illustrates the antimicrobial mechanisms of action of nanocomposites designed for food packaging.[96]

Bio-nanocomposites represent a fusion of biopolymers and nanomaterials, resulting in materials that combine the benefits of both worlds. Biopolymers, sourced from renewable resources, reduce the environmental impact associated with conventional plastics.

3.3. Carbon nanostructures in food packaging

3.3.1. Carbon dots. Fluorescent carbons, also known as carbon dots, exhibit a multitude of unique and exceptional properties, including high chemical stability, facile synthetic methods, and water solubility, among others. Their exceptional antibacterial properties can be attributed to the diverse functional groups present in them, such as –OH, –NH, and –COOH, alongside a carbon center. For instance, Raina *et al.*[97] demonstrated the antibacterial effect of Ag@CD against *Escherichia coli* and *Staphylococcus aureus* bacteria, utilizing Cannabis sativa leaves for the synthesis of carbon dots. Other researchers have employed the hydrothermal method to assess the antibacterial potential of N-doped CDs, utilizing *Osmanthus* leaves as a precursor for CD synthesis.[98]

Additionally, CDs can serve as effective and environmentally friendly active packaging materials. This application was verified through various experiments, including the fabrication of antimicrobial bacterial nanocellulose (BNC) sheets using CDs. Incorporating small-sized CDs (4–5 nm) derived from white mulberry into the BNC resulted in the production of nanopaper with strong antimicrobial and UV-blocking properties against *L. Monocytogenes*.[99] Similarly, CDs obtained from lactic acid bacteria were utilized by Kousheh *et al.*[100] to create a UV-protective and antimicrobial bacterial nanocomposite film, exhibiting notable mechanical and antimicrobial activities against *L. monocytogenes* and *E. coli*.

The potential applications of carbon dots as additives, coating agents, and active and intelligent agents for food packaging purposes are illustrated in Fig. 15.[101] Furthermore, Fig. 16 (ref. 101) delineates the ultraviolet light barrier mechanism of carbon dots-based biodegradable packaging, highlighting their role in safeguarding food products from ultraviolet radiation.

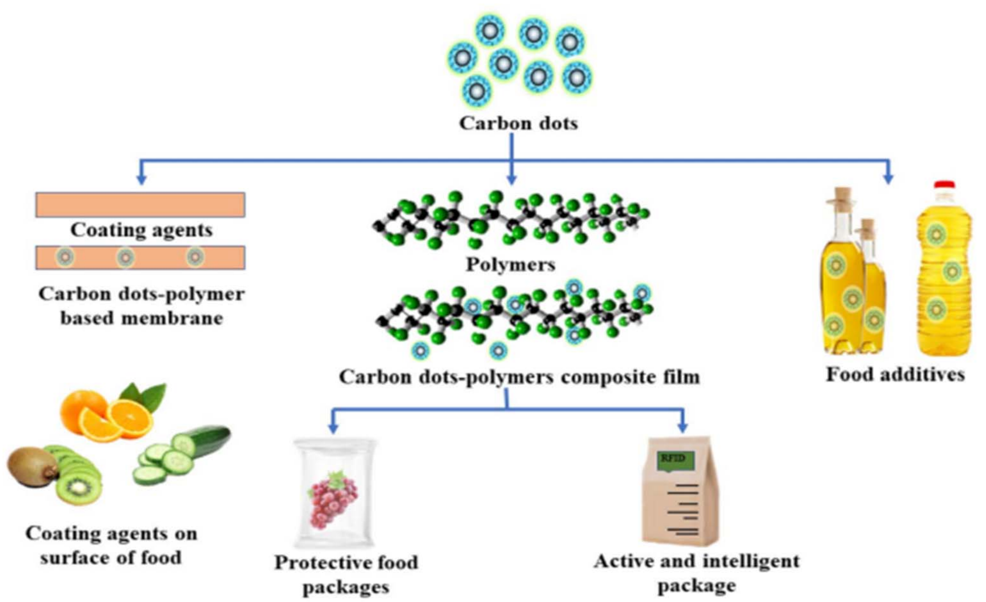

Fig. 15 Potential applications of carbon dots as additives, coating agent, and active and intelligent agents for food packaging applications.[101]

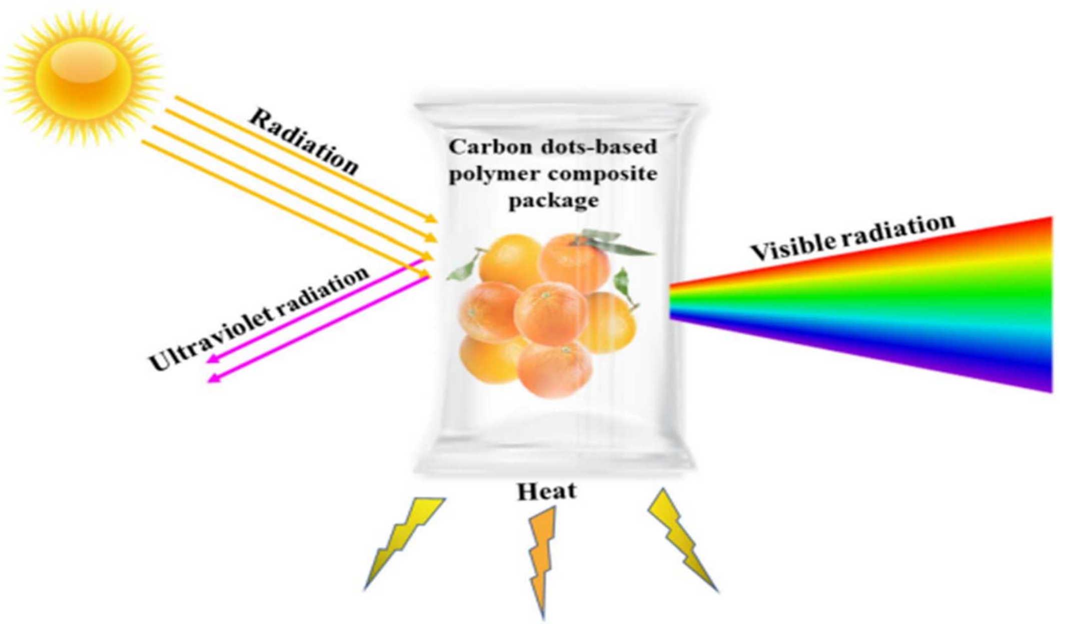

Fig. 16 Ultraviolet light barrier mechanism of carbon dots based on biodegradable packaging illustrating food product's protection from ultraviolet radiation.[101]

3.3.2. Carbon nanotubes. One-dimensional carbon nanomaterials are divided into two categories: single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs).[102] SWCNTs consist of a single layer of graphene rolled into a cylinder, while MWCNTs are characterized by a coaxial arrangement of multiple concentric cylindrical shells around a central hollow core, held together by van der Waals forces between adjacent layers.[103] Extensive research has investigated the antibacterial properties of carbon nanotubes. For instance, Ag-doped TiO_2 nanoparticles with SWCNTs and MWCNTs coatings were synthesized, and their antibacterial efficacy against *S. aureus* and *E. coli* was studied, revealing that SWCNTs-TiO_2/Ag exhibited greater toxicity than MWCNTs-TiO_2/Ag.[104]

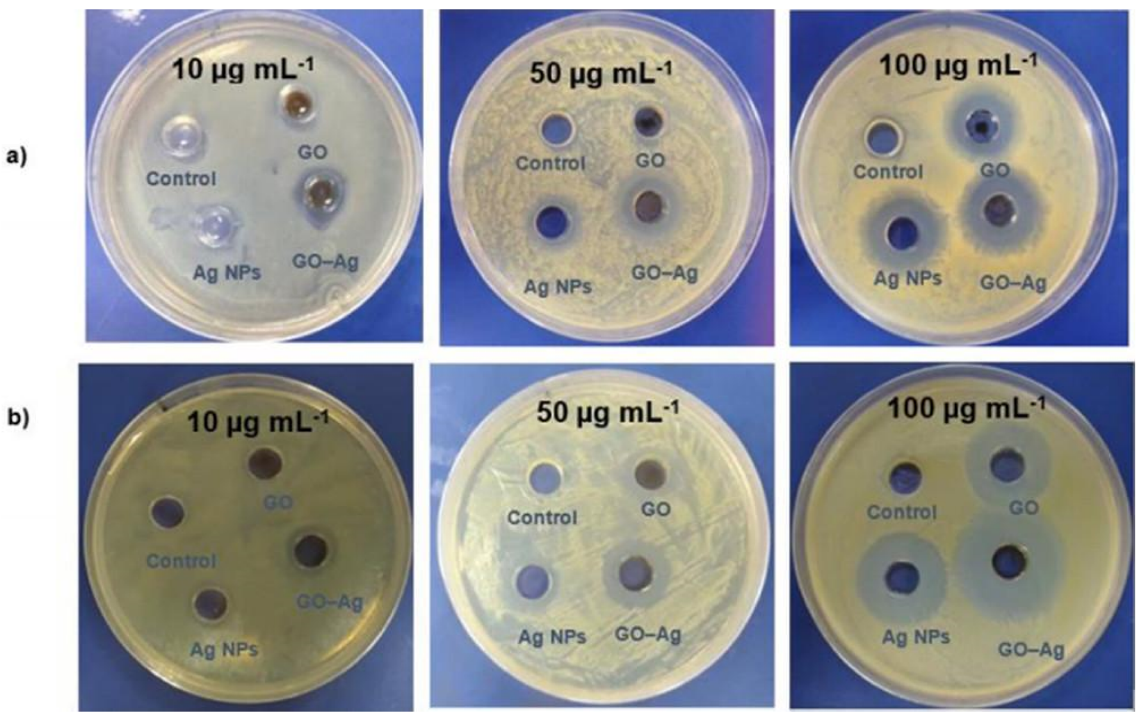

Fig. 17 Zone of inhibitions displayed by control, GO, Ag NPs, and GO-Ag against (a) *E. coli* and (b) *S. aureus*.[110]

Moreover, carbon nanotubes have found applications in food packaging materials. Incorporating CNTs into bionanocomposites of poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) has significantly enhanced the mechanical and thermal properties, as well as the tensile strength and Young's modulus, of the resulting films.[105] These improved properties have contributed to their widespread use as food preservatives and packaging materials. Additionally, films made using carbon nanotubes and isothiocyanate have been employed for the packaging of shredded and cooked chicken meat.[106] CNTs have also been utilized in the production of garlic-microparticle-coated gelatin/MWCNT nanocomposite films for use as food packaging material.[107]

3.3.3. Graphene-based nanomaterials. Numerous research studies have focused on examining the antibacterial properties of nanomaterials based on graphene. For instance, the antibacterial effects of graphene oxide (GO) nanosheets against both Gram-negative and Gram-positive bacteria have been investigated, revealing distinct zones of inhibition in comparison to commercially available antibiotics.[108] Notably, the zones of inhibition demonstrated by GO were as follows: *E. coli*, 39 mm; *S. aureus*, 38 mm; *K. pneumoniae*, 41 mm; *P. aeruginosa*, 38 mm; *S. marcescens*, 39 mm; and *P. mirabilis*, 27 mm. Enhanced antibacterial activity was observed in GO synthesized *via* the modified Hummers' method, surpassing the effectiveness of all the tested commercial antibiotics. Other studies on the antimicrobial properties of graphene-based nanomaterials have similarly presented promising findings.[109–111]

In another study by Vi *et al.*, the antibacterial activity of Ag-GO against *S. aureus* and *E. coli* was investigated, revealing that Ag-GO exhibited 73% inhibition against *E. coli* and 98.5% inhibition against *S. aureus* when compared to pristine GO and silver nanoparticles.[110] Fig. 17 illustrates the different zones of inhibition.[110]

In contemporary times, graphene-based nanomaterials have also found utilization as biofiller materials. For instance, GO/polylactic acid films[111,112] have been employed as food packaging materials, demonstrating antibacterial activity against *S. aureus* and *E. coli*. Likewise, Ag–ZnO-rGO/polyethylene nanocomposite films,[113] MTAC-rGO-EVOH films,[114] starch-reduced graphene oxide/polyiodide nanocomposite films,[115] thermally exfoliated graphene oxide reinforced polycaprolactone-based bactericidal nanocomposite films,[116] and various others are extensively employed in the food packaging industry, showcasing antibacterial properties alongside their potential as effective food packaging materials. The process of forming films using carbon-based nanomaterials is illustrated schematically in Fig. 18.[117]

Nanomaterials, such as carbon nanotubes and graphene, enhance mechanical properties and offer unique functionalities. The integration of nanomaterials into bio-based matrices improves packaging strength, barrier properties, and even sensor capabilities. Carbon nanotubes, known for their exceptional mechanical strength, reinforce packaging materials without compromising their biodegradability. Graphene, with its high electrical conductivity, opens doors to smart packaging that can monitor food quality in real time. These innovations promote sustainability by enabling packaging manufacturers to create thinner and lighter materials while maintaining desired properties. Reduced material consumption translates to lower resource use and transportation costs, thereby minimizing the environmental footprint of packaging.

Fig. 19 represents applications of nanoparticles in food packaging[118] and various nanomaterials which are used in food packaging industry are discussed below.

3.4. Nanomaterials in food packaging

3.4.1. Nanocellulose. Cellulose, a polysaccharide abundantly present in nature and a key component of plant cell

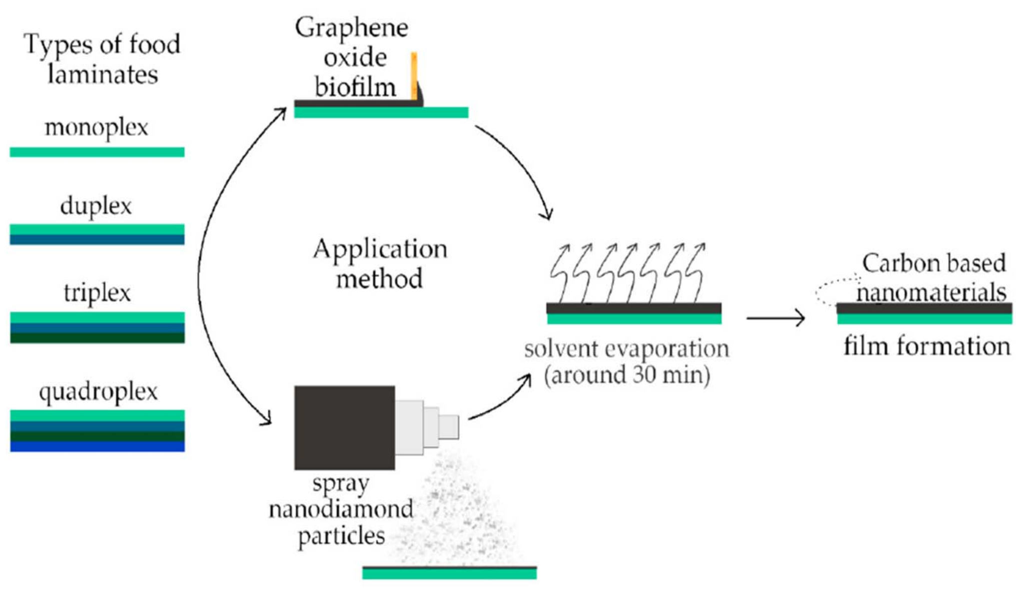

Fig. 18 Schematic representation of the carbon based nanomaterials film formation.[117]

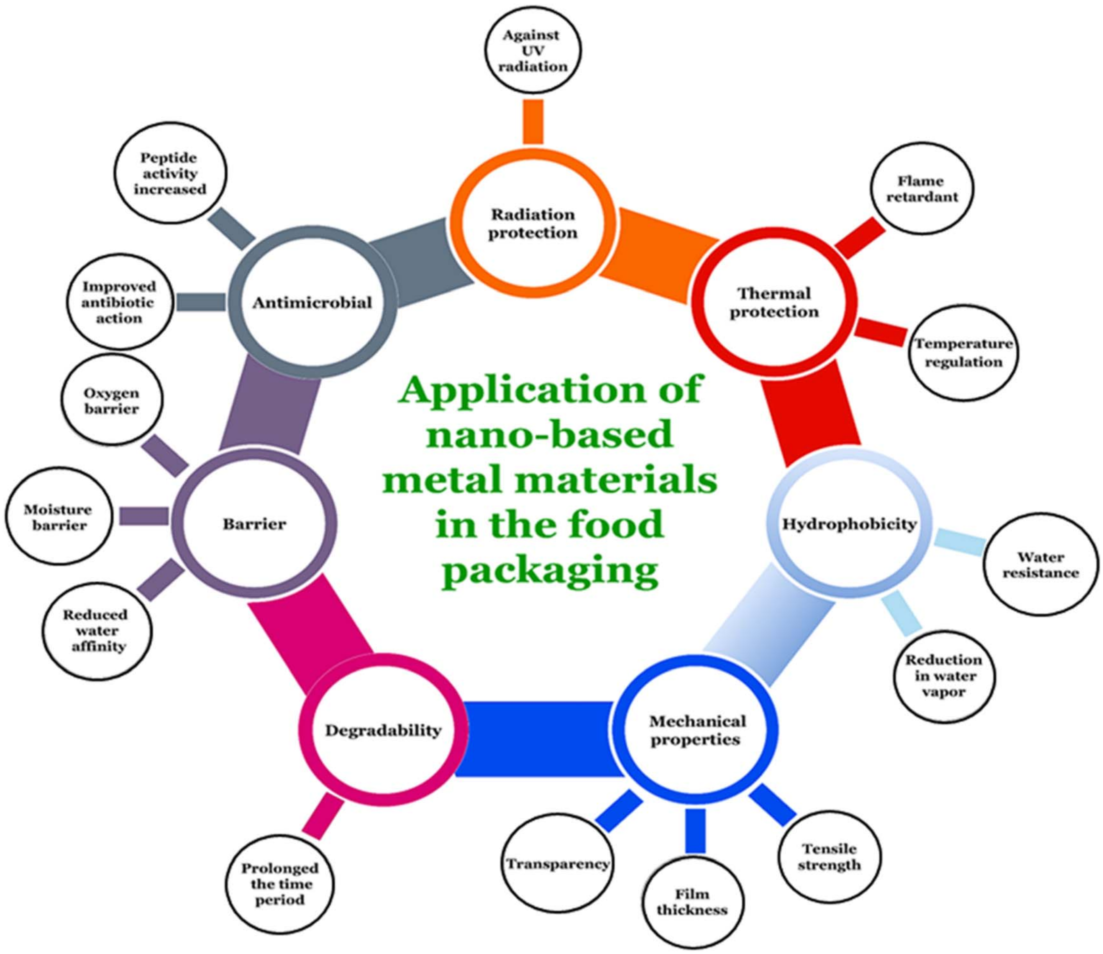

Fig. 19 Applications and characteristics of nano-based metal-materials in food packaging.[118]

walls, plays a critical role in providing structural integrity to plant cells. Nanocellulose, with a nano-sized cellulose structure, can exist as either nanocrystals or nanofibers, characterized by a diameter of less than 100 nm and lengths of a few micrometers.[119] Chemical and mechanical extraction processes enable the retrieval of nanocelluloses from plants, facilitating the creation of dense, impermeable surfaces for molecules owing to their remarkable hydrogen bonding capability. This unique property of nanocellulose contributes to its excellent barrier properties.[120] The widespread use of nanocellulose in the paper and composite industries serves to enhance uniformity, biodegradability, strength, and mechanical properties.[121] Incorporating nanocellulose into biopolymers presents challenges due to the interfacial disparities between the two constituents; however, successful integration leads to improved mechanical, thermal, and barrier properties.[122]

3.4.2. Nano starch. The intricate polysaccharide starch is comprised of two polymers, namely amylose and amylopectin, and can be generated through diverse physical and chemical treatments involving the breakdown of starch granules.[123] These nanoparticles possess a substantial surface area per unit volume and have at least one dimension smaller than 300 nm.[124] Employed as nanofillers, starch nanoparticles/starch nanocrystals serve to enhance the biodegradability, thermal and water impermeability, strength, flexibility, and barrier properties of composites.[125,126]

3.4.3. Protein nanoparticles. Protein-based nanoparticles significantly contribute to bolstering the barrier properties, such as water resistance and strength, of food packaging materials.[127] Incorporating peanut protein nanoparticles into protein-starch-based biocomposites was observed to enhance their strength, moisture barrier properties, and temperature resistance.[128] Similarly, the incorporation of zein nanoparticles into whey isolate-based films was found to enhance their moisture barrier and mechanical properties.[129]

3.4.4. Silver nanoparticles. Silver nanoparticles (AgNPs) play a crucial role as antimicrobial agents in food packaging, contributing to the enhancement of food shelf life. They exhibit antibacterial activity against a variety of Gram-negative and Gram-positive bacteria, in addition to possessing antioxidant properties. Due to these distinct features, researchers have developed environmentally friendly, cost-effective, and straightforward processes for their synthesis.[130] AgNPs serve as antimicrobial agents in both biodegradable and non-biodegradable polymers for the production of active food packaging films.[131] When incorporated into food packaging materials after necessary modifications so as make them safe and non-toxic, silver nanoparticles gradually release into food products, acting against microbes and mitigating food toxicity.[132,133] They can also be embedded in active packaging films and coatings, which then release onto the food surface, effectively inhibiting microbial growth and extending food shelf life, as the food surface is considered a hotspot for microbial activity initiation. These techniques have the potential to reduce the use of preservatives, which may be harmful, contributing to the extension of shelf life and maintenance of food quality.[134]

3.4.5. Zinc oxide nanoparticles. Zinc, an essential micronutrient, holds a significant role in the formulation of dietary supplements and fortified foods.[135] When present in the form of ZnO nanoparticles, it generates Zn^{2+} ions and reactive oxygen species (ROS), which can harm cell organelles and lead to cell death. This property makes it a valuable antibacterial agent effective against a wide range of bacteria such as *E. coli*, *Listeria monocytogens*, *Staphylococcus aureus*, *Salmonella enteritids*, among others.[136] When incorporated into the polymer matrix of composite films, these nanoparticles contribute to the enhancement of the mechanical, antimicrobial, and barrier properties of the films.[136,137] Their ready availability in highly pure form on the market makes it easy to study their effects by integrating them into various polymer matrices.[137]

3.4.6. Titanium dioxide nanoparticles. TiO_2 nanoparticles, white-colored metal oxides, are utilized in various food industry applications, including food additives, and are also employed as nanocomposites in packaging.[138] Their incorporation into food packaging polymers serves to block UV radiations while simultaneously enhancing the mechanical, chemical, and barrier properties of the resulting food packaging films. Due to their distinctive characteristics such as color stability, high index of refraction, and brightness, TiO_2 NPs are also used as coloring agents in various processed foods.[139,140] Additionally, they exhibit antimicrobial properties as they generate free radicals and reactive oxygen species (ROS) upon interaction

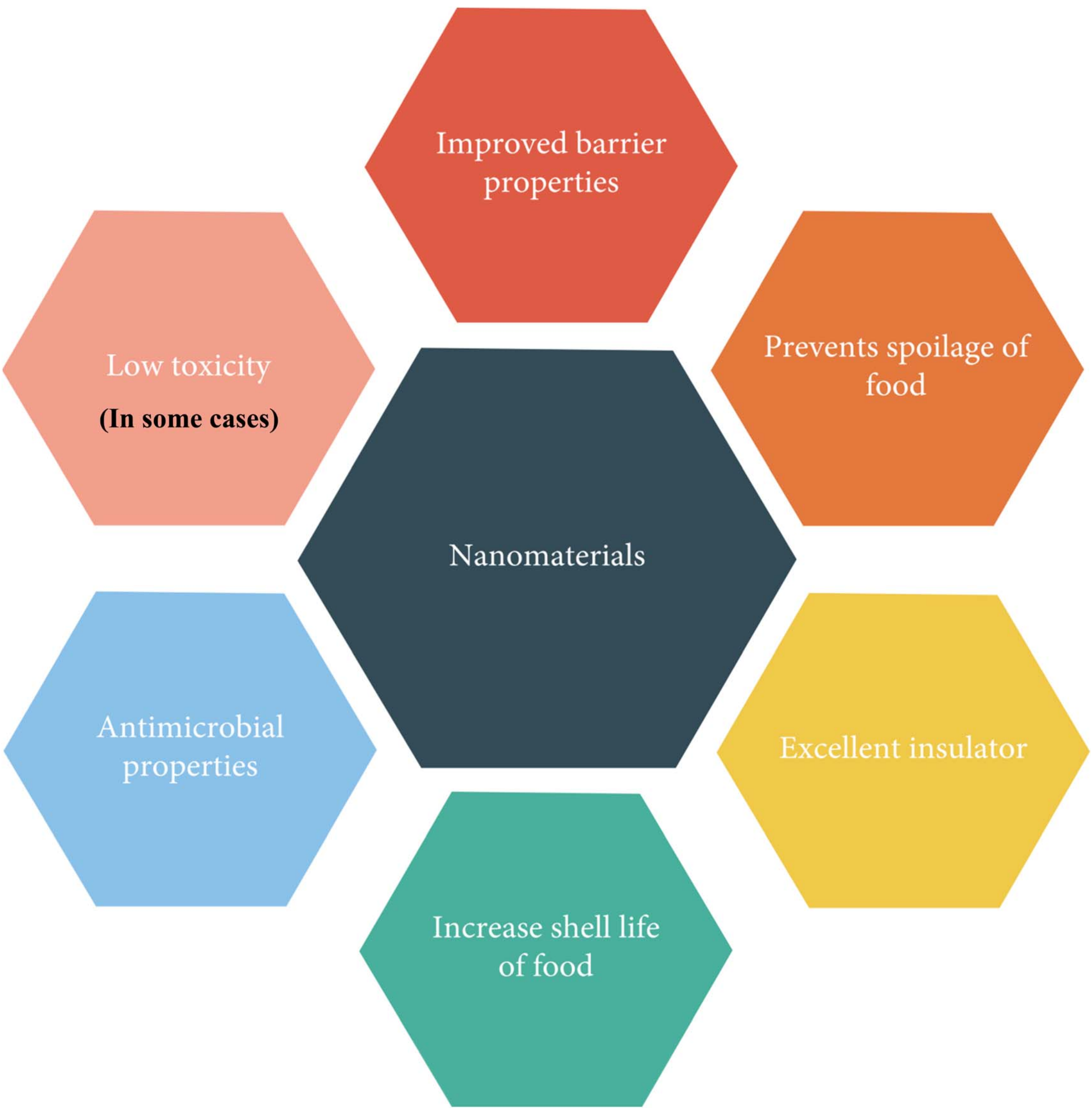

Fig. 20 Properties of nanomaterials.[146]

with bacterial cells, leading to cell death.[141] Owing to their environmentally friendly nature, chemical stability, cost-effectiveness, and non-toxicity, they are effective photocatalysts.[138] When exposed to sunlight, TiO_2 facilitates the photodegradation of ethylene, making it useful as an oxygen and ethylene scavenger.[142]

3.4.7. Nanoclay. Nanoclay, a layered mineral silicate composed of octahedral and/or tetrahedral sheets, contributes to the enhancement of the physical and barrier properties of plastic food packaging materials.[143] Its inclusion in these materials results in improved barrier and mechanical properties of thermoplastics, while also enhancing the biodegradability of synthetic polymers.[144–147]

The suitability of nanomaterials for food packaging applications is underscored by their various properties, as depicted in Fig. 20.[146]

Nanoclays and other nanomaterials offer a range of advantages, including enhanced mechanical strength, barrier properties, and thermal stability when incorporated into various products. They can improve the durability and performance of materials such as packaging, construction materials, and automotive components. Additionally, nanomaterials often enable the development of novel functionalities, such as antimicrobial properties or self-healing capabilities, which can contribute to product innovation and sustainability efforts. Moreover, nanotechnology holds promise for advancements in fields like medicine and renewable energy, with potential applications in drug delivery systems, diagnostics, and efficient energy storage.

However, alongside these benefits, there are also notable concerns associated with the use of nanomaterials. One significant issue is the potential environmental impact, particularly when nanomaterials are released during the biodegradation of products containing them. Questions arise regarding the effects of nanoparticles on soil microorganisms and ecosystems, including their potential toxicity and long-term consequences. Furthermore, the behavior and fate of nanoparticles in the environment are still not fully understood, raising uncertainties about their ecological footprint and potential risks to human health through exposure pathways.

Additionally, the manufacturing processes involved in producing nanomaterials may have environmental implications, such as energy consumption, resource depletion, and waste generation. Concerns have been raised about the possible release of harmful by-products or contaminants during the synthesis and disposal of nanomaterials. Furthermore, there are regulatory and ethical considerations surrounding the use of nanotechnology, including questions about safety standards, risk assessment methodologies, and public perception.

Overall, while nanomaterials offer exciting possibilities for technological advancement and innovation, it is essential to carefully weigh their potential benefits against the associated risks and challenges. Effective risk management strategies, comprehensive environmental assessments, and transparent communication are crucial for ensuring the responsible development and utilization of nanotechnology in a manner that promotes sustainability and minimizes adverse impacts on human health and the environment.[148]

The impact of nanomaterials on microorganisms in soil is a complex and multifaceted issue that requires careful consideration. Some studies suggest that certain nanoparticles may have antimicrobial properties, potentially inhibiting the growth or activity of soil microorganisms. This could disrupt crucial ecological processes such as nutrient cycling and soil fertility, ultimately affecting plant health and ecosystem stability. On the other hand, nanomaterials might also interact with soil microorganisms in ways that enhance their growth or metabolic activity, leading to beneficial effects such as improved soil structure or enhanced degradation of organic pollutants.

However, the specific effects of nanomaterials on soil microorganisms can vary widely depending on factors such as nanoparticle composition, size, surface properties, and environmental conditions. Additionally, there is still limited research on the long-term consequences of nanoparticle exposure on soil microbial communities and ecosystem functioning. It is crucial to conduct further studies to better understand the mechanisms underlying nanoparticle–microorganism interactions and to assess the potential risks and benefits associated with the widespread use of nanomaterials in agriculture, construction, and other sectors. Ultimately, sustainable management practices and regulatory measures may be necessary to minimize any adverse impacts on soil microbial communities while maximizing the potential benefits of nanotechnology.[149]

Nanomaterials have ushered in a new era of tailored packaging solutions with improved functionalities. Nano cellulose, extracted from plant sources, enhances packaging strength and reduces oxygen permeability. Nano starch, derived from agricultural waste, improves mechanical properties and offers biodegradability. Furthermore, nanomaterials like protein nanoparticles, silver nanoparticles, zinc oxide nanoparticles, and titanium dioxide nanoparticles provide unique benefits. Protein nanoparticles can improve packaging strength and act as carriers for bioactive compounds. Silver nanoparticles offer antimicrobial properties, which can extend the shelf life of perishable foods. Zinc oxide and titanium dioxide nanoparticles contribute to UV-blocking and antimicrobial effects, reducing the need for synthetic additives. These advancements promote sustainability by enhancing packaging performance and reducing the reliance on synthetic materials and additives, thus aligning with consumer demands for cleaner and safer packaging.

3.5. Antimicrobial packaging

One of the primary factors contributing to the spoilage of food products is the undesirable proliferation of pathogenic and spoilage microorganisms. To counter this issue, one of the crucial strategies involves the use of antimicrobial materials, such as active substances like absorbent pads and emission sachets, among others. Most antimicrobial active encapsulation systems are formulated using compounds such as triclosan, chlorine dioxide, glucose oxidase, silver, silver zeolite,

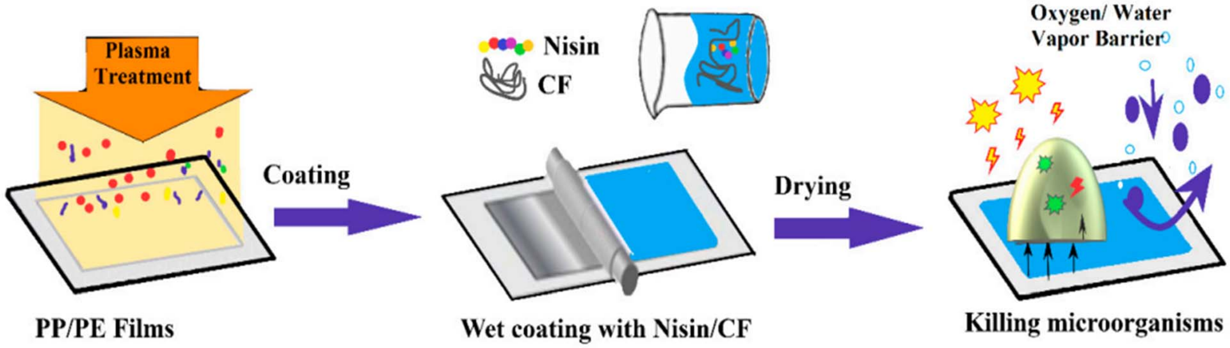

Fig. 21 Coating of polypropylene/polyethylene (PP/PE) films with other polymers (cellulose fibers—CF) and loading with antibacterial agents (nisin).[152]

natamycin, ethanol vapor emissions, allyl isothiocyanate, and sulfur as active components.[150,151] Notably, silver, platinum, gold, and copper are some of the key examples of antimicrobial agents.

Fig. 21 illustrates the coating of polypropylene/polyethylene (PP/PE) films with other polymers (cellulose fibers—CF) and their loading with antibacterial agents (nisin).[152] Various techniques related to antimicrobial packaging are outlined below.

3.5.1. Packaging with CO_2 emitters.

CO_2 is both water-soluble and lipid-soluble in food. This leads to the creation of carbonic acid, which subsequently causes the acidification of food products. Its role in the food industry is multifaceted, serving to preserve food quality and extend shelf life. The effects of CO_2 on food are complex, involving alterations to bacterial cell membranes, inhibition of bacterial enzymes, and changes in cytoplasmic pH. These actions result in the extension of the

Fig. 22 Commonly used antimicrobial agents in food packaging applications.[157] Reproduced (adapted) with permission from ref. 157. Copyright [2021] [Elsevier].

lag phase and the suppression of the growth of numerous spoilage microorganisms.[153]

In the domain of CO_2 emission technologies, baking soda ($NaHCO_3$) and organic acids stand out as two common active ingredients. Additionally, citric acid can serve as a CO_2 emitter. Combinations of various active substances, such as the amalgamation of ascorbic acid and iron carbonate, can also yield CO_2 emission, along with the simultaneous consumption of O_2 in a 1 : 1 ratio.[154–156]

Fig. 22 illustrates commonly used antimicrobial agents in food packaging applications.[157]

Antimicrobial substances, such as disinfectants and antibiotic drugs, are crucial for preventing and treating infections but face challenges due to antimicrobial resistance, with nearly 5 million deaths attributed to this issue in 2019. The use of disinfectants and cleaning products is increasingly recognized as a contributor to antimicrobial resistance alongside human and veterinary medicine. Certain microorganisms develop tolerance to these substances, particularly at sublethal concentrations, through mechanisms like spore formation and changes in cell membrane composition. *Pseudomonas* species, notably *Pseudomonas aeruginosa*, pose significant challenges due to their efflux pumps and ability to tolerate disinfectants like benzalkonium chloride (BAC). Resistance can extend to clinically relevant antibiotics and is influenced by environmental factors, such as the presence of other microorganisms. Studies have shown that exposure to disinfectants can enrich antimicrobial resistance genes in soil microbial communities, highlighting the need for cautious use of these substances. Moreover, antimicrobial resistance exacerbates concerns, particularly in drug-resistant pathogens like *P. aeruginosa*, with potential links to increased antibiotic resistance observed following the COVID-19 pandemic. These findings underscore the importance of judicious disinfectant use and vigilant monitoring to mitigate the spread of antimicrobial resistance. The potential consequences of using antimicrobial materials to prevent food waste and extend shelf life, it becomes evident that the focus on food safety must be balanced with consideration for broader environmental impacts. While antimicrobial materials play a crucial role in inhibiting the growth of harmful microorganisms, they can inadvertently affect beneficial microorganisms present in food, the human gut, and soil ecosystems. These beneficial microorganisms are essential for processes such as fermentation, digestion, and nutrient cycling, contributing to both human health and environmental sustainability. Therefore, the indiscriminate use of antimicrobial materials may disrupt these delicate microbial ecosystems, potentially leading to unintended consequences for both human and environmental health.

Moreover, the impact of antimicrobial materials extends beyond their immediate application in food packaging to their entire life cycle. Concerns have been raised regarding the biodegradability of these materials, particularly in ambient environments where conditions may differ from controlled laboratory settings. Various studies have highlighted discrepancies between biodegradability claims and actual environmental degradation rates, indicating the need for more rigorous evaluation and regulation of such materials. False certifications and claims regarding biodegradability not only mislead consumers but also contribute to environmental pollution and the accumulation of non-biodegradable waste.

Therefore, it is imperative to adopt a more holistic approach to food packaging design, one that considers the potential impacts of antimicrobial materials on microbial ecosystems, human health, and environmental sustainability throughout their entire life cycle. This approach involves not only evaluating the efficacy of antimicrobial materials in preventing food waste and extending shelf life but also assessing their long-term environmental consequences, including their biodegradability and potential for unintended ecological disruption. By integrating considerations for microbial ecology, environmental degradation, and regulatory oversight, we can develop more sustainable solutions for food packaging that prioritize both food safety and environmental stewardship.[158,159]

Antimicrobial packaging tackles two critical aspects of food preservation: extending shelf life and reducing the need for chemical additives. Packaging integrated with carbon dioxide emitters or scavengers modifies the package atmosphere, inhibiting microbial growth and delaying spoilage. Antioxidant agents incorporated into packaging materials prevent oxidative reactions, maintaining food quality. By employing these technologies, antimicrobial packaging reduces the likelihood of premature spoilage, thereby minimizing food waste. This aligns with sustainability goals by enhancing the efficiency of the food supply chain and reducing the environmental impact associated with discarded food. Biosensors integrated into packaging materials introduce a new dimension of functionality by allowing real-time monitoring of food quality.

3.6. Biosensor in food packaging

It is well understood that a wide array of chemical sensors is accessible for implementation in food packaging. However, in the case of biosensors, the situation differs significantly, with only a limited range finding application as intelligent food packaging materials. Among the most frequently utilized biosensors for active packaging are those designed for the direct detection of bacteria, necessitating contact with the food products (or the fluid form of food), as well as sensors for identifying volatile chemicals produced during the degradation of food products, among other functions.[160] Some of the most commonly employed biosensors in food packaging are listed below.

3.6.1. Fluorescent and microfluidics biosensors. Utilizing a solid polymer matrix in a biosensor centered on fluorescence enables the immobilization of bioluminescent or fluorescent dyes. Biosensor devices are constructed with a thin film incorporating a polymer coating of a distinct color. The luminous sensor's sensing coating operates in the presence of molecular oxygen emitted from the headspace of the package, employing a straightforward diffusion technique that facilitates a flexible light washout. The calibration curve's effects on various luminescence parameters aid in the determination of oxygen concentration.[161] In this reversible technique, the fluorescence-based oxygen sensor does not yield any by-products or consume dyes during the process. Moreover, the fluorescent-based biosensors generate an array of colors upon encountering food pathogens. They can also function as electronic noses or tongues, contributing to a reduction in pathogen detection time from hours to days. Their compact size is advantageous in detecting minute substances in large volumes over time.[162]

3.6.2. Electrochemical biosensors. Presently, electrochemical biosensors are extensively employed for assessing food quality based on their functionalities. Based on biological recognition, electrochemical biosensors primarily fall into two categories: affinity-based biosensors and biocatalytic sensors. Biocatalytic biosensors are utilized for identifying target biomolecules, employing redox enzymes, tissue slices, or entire cells as recognition materials in the process.[163] In affinity-based sensors, recognition materials include antibodies, aptamers, and antibody fragments. The distinctive properties and benefits of biocatalytic biosensor devices, such as their uncomplicated design, ease of use, cost-effectiveness, compact size, and frequently absent additional equipment, make them readily adaptable with packaging materials.[164] Additionally, these biosensors demonstrate exceptional specificity for the target substance, obviating the need for pretreatment or separation processes. Advantages of electrochemical biosensors include lower detection limits, reduced background signal, and a straightforward sensor approach.

One prominent instance of an electrochemical biosensor for foods documented in the literature is the biosensor based on single-walled carbon nanotubes (SWCNT) for detecting food microbes.[165,166] Other examples of electrochemical biosensors involve a biosensor relying on diamine oxidase for amine measurements in packed food present in the atmosphere, as well as a biosensor centered on DNA for detecting potential carcinogens in food samples.[167]

3.6.3. Gas sensors. Gas sensors are instrumental in detecting gas leaks in packaging and assessing food quality. They also aid in identifying the presence of spoilage gases, such as basic oxygen, nitrogen compounds, and carbon dioxide, which are emitted during food spoilage.[168] Moreover, they can be employed for detecting pesticides like carbamides in fruits and vegetables, serving as a rapid, sensitive alternative for testing the rancidity of meat products. A gas sensor typically comprises three components: the sensing electrode, the counter electrode, and the reference electrode. This sensor operates based on the detection of CO_2 compounds within food containers. It exhibits robust functionality even in hazardous environments and specifically targets gas molecules, remaining unaffected by electromagnetic interferences. These distinct characteristics of gas sensors position them as pivotal choices

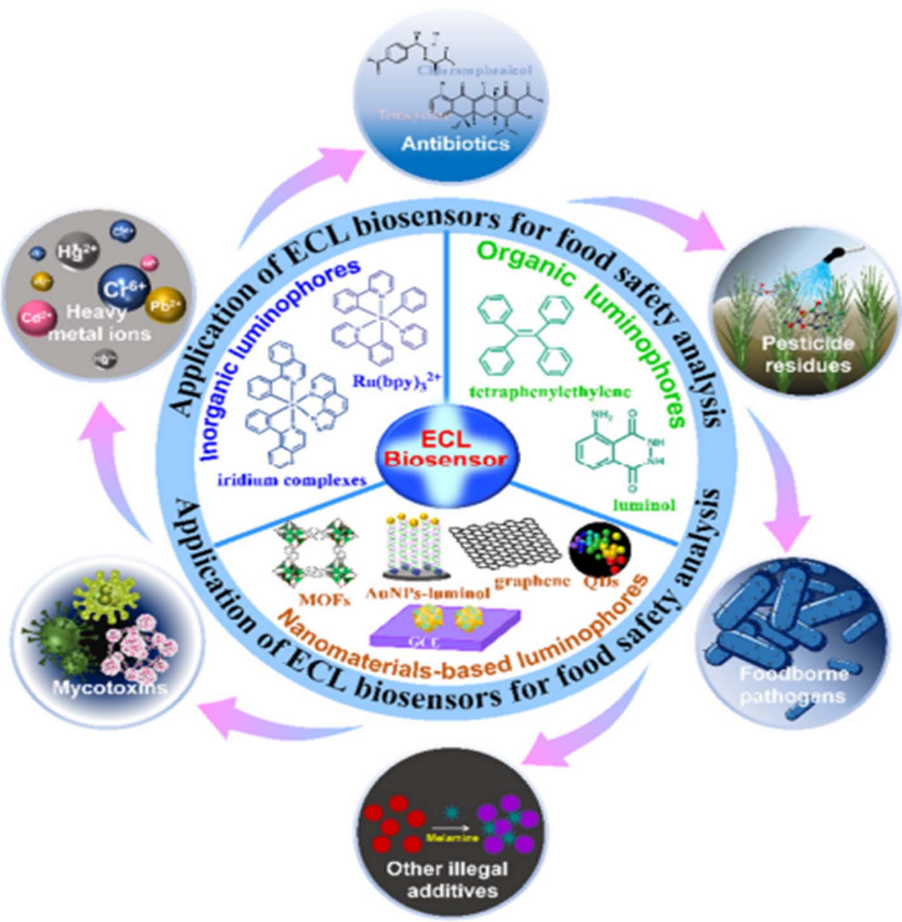

Fig. 23 Principles of ECL biosensors, ECL luminophores, and their ECL applications in food analysis.[170]

for the food packaging industry.[169] Fig. 23 illustrates the principles of ECL biosensors, ECL luminophores, and their ECL applications in food analysis.[170] We can incorporate such sensors in food packaging materials for advanced applications.

Fluorescent and microfluidics biosensors detect specific spoilage indicators, providing consumers with timely information about food freshness. Electrochemical biosensors gauge freshness based on parameters like pH and gas emissions. These biosensors empower consumers to make informed decisions about the safety and quality of their food purchases. By reducing instances of consuming spoiled food, biosensors contribute to sustainability by reducing food waste and encouraging responsible consumption.

3.7. Chitosan-based films for food packaging

Chitosan-based films have been the subject of extensive research for several years due to their distinctive and significant applications in the food industry, contributing to the reduction of environmental impacts.[171–173] These films serve as effective food packaging materials, aiding in the extension of the shelf life of food.[174–189] Various types of chitosan-based films are utilized in the realm of the food packaging industry, offering diverse applications.

3.7.1. Chitosan/biopolymer-based films. Due to their distinct and significant characteristics, naturally derived biopolymers are suitable for blending with chitosan to create chitosan/biopolymer films. These biopolymers, which include polysaccharides, organic acids, extracts, proteins, among others, offer attributes such as nontoxicity, biocompatibility, and biodegradability. The resulting films have found significant applications in the food packaging industry.[190]

3.7.2. Chitosan/polysaccharides-based films. Composite films with chitosan can be created by combining polysaccharides, resulting in functional films. Starch, a renewable polysaccharide derived from plants, is one of the most important options due to its widespread availability, low cost, and film-forming capability. The resulting composite films with chitosan exhibit distinct properties, including notable antioxidant activity, improved water vapor barrier properties, and reduced bacterial adhesion on the packaging, making them highly effective for food packaging applications.[191–193] Numerous researchers have reported that cellulose/chitosan films offer enhanced mechanical properties, which can be attributed to the hydrogen bonds between the nanocellulose and chitosan. These films also demonstrate excellent antimicrobial, gas barrier, optical, and bioactive properties, alongside sustainability.[194–198] Additionally, the chitosan/carboxymethyl film, formed through electrostatic interactions, has been shown to extend the shelf life of wheat bread and cheese.[199,200] Other cellulose materials, such as chitosan/alginate, chitosan/pectin, and chitosan/cyclodextrin, can also be utilized to synthesize composite films with chitosan, offering diverse applications and properties.[201–211]

3.7.3. Chitosan/protein-based films. An array of proteins sourced from plants, animals, and microorganisms can be blended with chitosan to create films. These chitosan/protein films possess distinct functional groups that enable them to be applied in various areas, including food packaging.[212–225] Proteins derived from animals, in particular, have garnered significant interest in research due to their notable properties such as film-forming ability, biocompatibility, and high nutritive value. Several proteins exhibit these unique attributes, allowing them to be combined with chitosan to produce films with diverse functionalities in food packaging. Notable examples include chitosan/caseinate, chitosan/collagen, chitosan/lysozyme, chitosan/gelatin, chitosan/kidney bean protein, chitosan/quinoa protein, chitosan/nisin, and chitosan/ε-polylysine/nisin films.[212–225] These chitosan-based films serve various purposes in the food packaging industry, acting as antimicrobial agents, extending the shelf life of food, and improving food quality, among other functions.

3.7.4. Chitosan/extracts-based films. Chitosan can be combined with extracts from bee secretions, such as beeswax and propolis, to produce films for food packaging.[226] Chitosan/beeswax films are known for their environmentally friendly nature and their ability to regulate pathogenic microorganisms while preserving food quality.[227,228] Natural and non-toxic extracts from plants have been utilized in the food industry for decades, particularly in food preservation. When incorporated into chitosan films, these plant extracts significantly enhance various properties, including antimicrobial activity (*e.g.*, honeysuckle flower and citrus extracts),[229,230] antioxidant activity (*e.g.*, clove eugenol and maqui berry extracts),[231,232] barrier performance (*e.g.*, thyme extract),[233] mechanical property (*e.g.*, tannic acid),[234] thermal stability (*e.g.*, young apple polyphenols),[235] and color property (*e.g.*, carvacrol).[236] Furthermore, the free radical-initiated grafting of gallic acid onto chitosan through carbodiimide (as shown in Fig. 24)[237,238] significantly enhances various film properties, including increased tensile strength, antioxidant capacity, and antimicrobial activity, as well as decreased oxygen and water vapor permeability.[237–241] This makes it an excellent candidate for multifunctional packaging applications in the food industry.

Plant-derived essential oils, known for their aromatic and volatile nature, can be extracted and incorporated into chitosan films, significantly enhancing their properties. For instance, films containing chitosan and cinnamon oil extract demonstrated remarkable antimicrobial efficacy, making them promising candidates for active food packaging.[242] Numerous other essential oils have also been shown to enhance various aspects of chitosan films, including barrier properties, mechanical properties, and antioxidant activity.[243,244]

3.7.5. Chitosan/synthetic polymers-based films. When chitosan is combined with synthetic polymers to create films, there is a notable enhancement in the properties and applications of the resulting films. Incorporating poly(vinyl alcohol), known for its robust mechanical strength, into chitosan facilitates the fabrication of films.[245] Higher concentrations of poly(vinyl alcohol) contribute to plasticization, increased elasticity, elevated tensile strength, and improved oxygen and water barrier properties in the films, which also exhibit potential antimicrobial activity in food packaging applications.[245,246] Incorporating or immobilizing certain bioactive materials in chitosan/poly(vinyl alcohol) films can imbue them with unique attributes such as mechanical

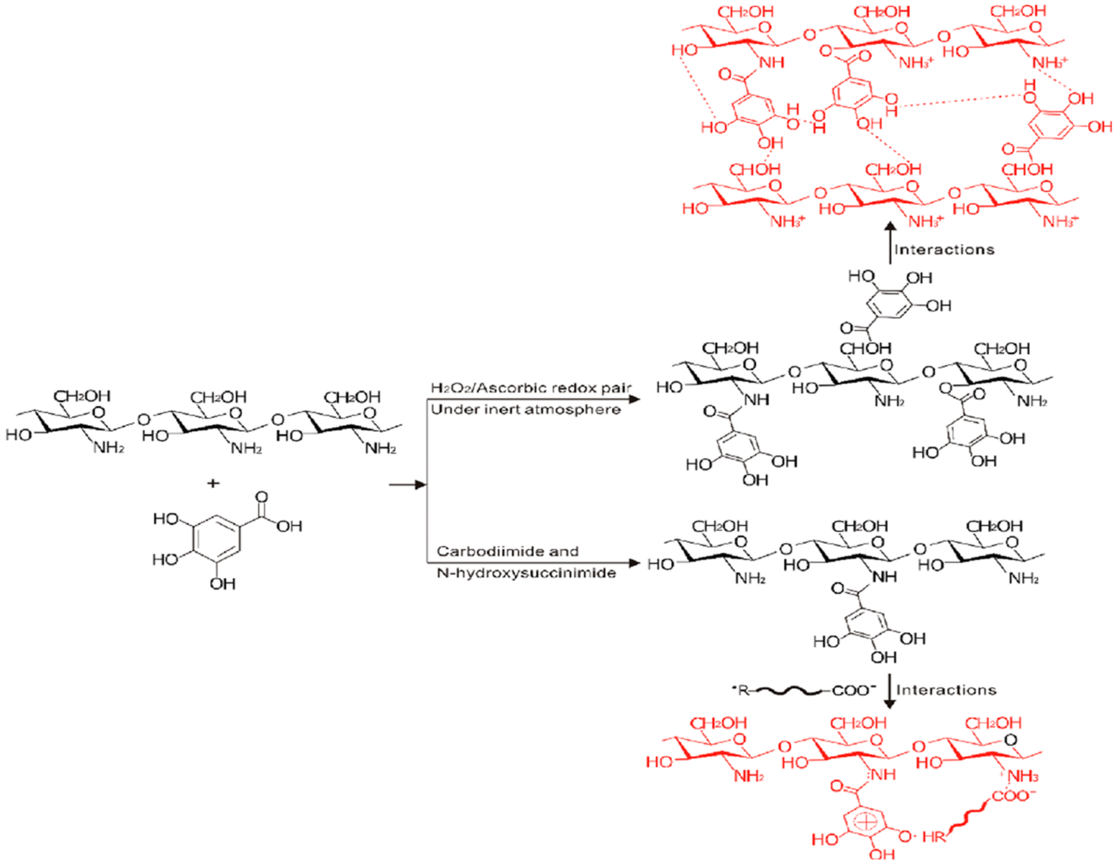

Fig. 24 Grafting of gallic acid onto chitosan.[196] Reproduced (adapted) with permission from ref. 196. Copyright [2014] [ACS].

durability and fire resistance, thereby broadening their potential applications.[247] Additionally, various other synthetic materials can be blended with chitosan films to enhance their characteristics and applications in the food packaging industry. Examples include chitosan/poly(lactic acid) films,[248,249] chitosan/salicylic acid films, chitosan/fumaric acid films,[250] chitosan/low-density polyethylene films,[251,252] chitosan/poly(ethylene oxide) films,[253] chitosan/allyl isothiocyanate films, and chitosan/polycaprolactone films.[254,255] Fig. 25 illustrates composite films with lactic acid oligomer-grafted chitosan as a nanofiller, demonstrating significant and promising enhancements in properties of food packaging materials, including tensile strength and thermal properties, through the use of such nanofillers.[256]

3.7.6. Chitosan/inorganic materials-based films. One of the most important characteristics of chitosan is their high chelating ability which makes it to be used for the synthesis of a large number of chitosan–inorganic complexes based films (Fig. 26). Such films can be widely used in food packaging applications.[197]

Given the antimicrobial effects of silver nanoparticles on various pathogenic microorganisms, they can be integrated into chitosan films for active use in food packaging. Employing green chemistry methodologies allows for the even distribution of chitosan and silver nanoparticles within the polymer matrix.[257,258] These films have numerous applications in edible food packaging due to the improved hydrophilic nature, antimicrobial activity, biocompatibility, non-toxicity, and degradability of chitosan and silver nanoparticles films.[259,260] Zinc oxide nanofillers are another material that enhances the biological and physicochemical properties, such as transparency, antimicrobial characteristics, and mechanical strength of composite films.[261,262] They prevent the growth of food pathogens and extend the shelf life of food, making them highly useful in the food industry.[263]

Graphene oxide and expanded graphite stacks also significantly enhance the properties of composite films compared to pristine chitosan films. These composite films, comprising graphene oxide, expanded graphite stacks, and chitosan, demonstrate improved mechanical capacity, oxygen barrier properties, and antimicrobial characteristics, making them valuable for food packaging.[264–267] The barrier properties, including oxygen, carbon dioxide, and water vapor properties, are greatly improved in chitosan/montmorillonite composite films.[268–271] Additionally, chitosan/montmorillonite composite films exhibit enhanced mechanical properties and improved flame-retardant characteristics, rendering them suitable for food packaging applications.[272–274] Incorporating various other inorganic materials into chitosan films also enhances their properties. Examples of these materials include silicon materials, titanium dioxide, nanomagnesium oxide, cloisite 20 A, $CaCO_3$, $CaCl_2$, cerium(IV), and zinc(II).[266,275–279] These chitosan/inorganic complexes based composite films possess unique and crucial attributes and applications, such as reducing the food decay rate, enhancing thermal stability, strengthening

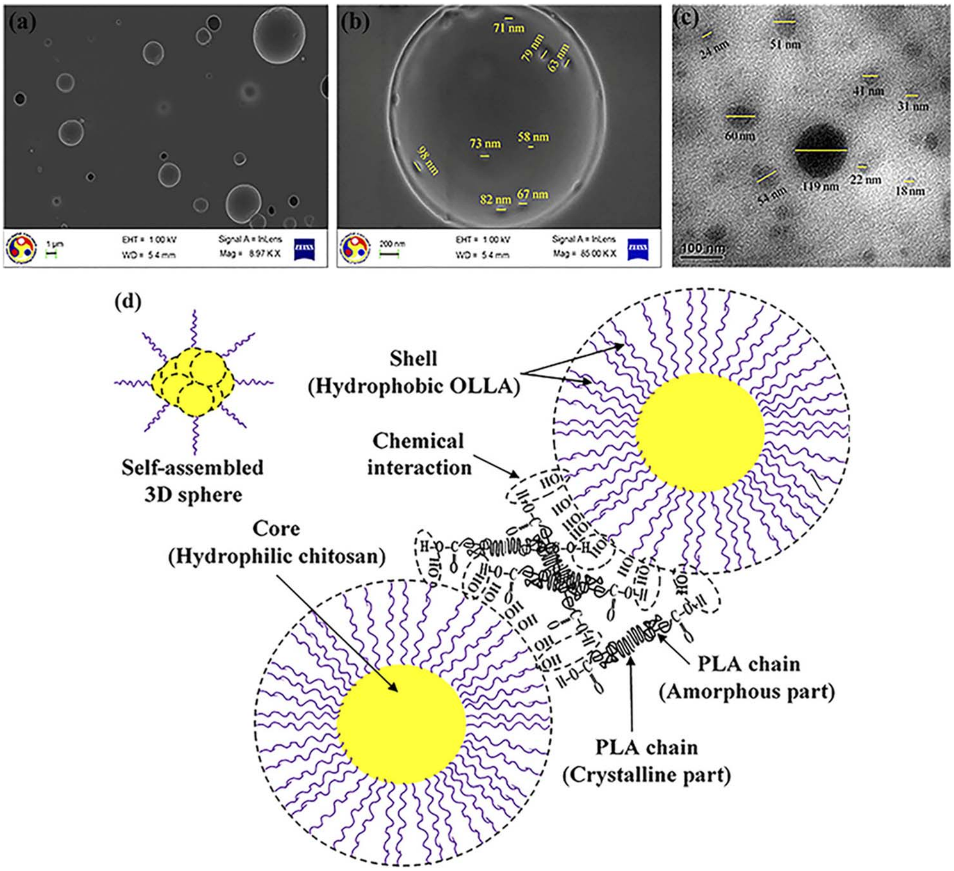

Fig. 25 FESEM images of PLA/OLLA-*g*-CH (5%) bionanocomposite film (a) at 8.97 KX, (b) at higher magnification ~85 KX, (c) TEM topography of PLA/OLLA-*g*-CH (5%) bionanocomposite film and (d) schematic representation of interaction between matrix and filler.[256] Reproduced (adapted) with permission from ref. 256. Copyright [2016] [ACS].

chemical resistance, and more, making them significant candidates for food packaging applications.[280–285]

3.7.7. Chitosan/chitosan derivatives-based films. Chitosan, which contains a significant number of hydroxyl and amino groups, can be transformed into chitosan derivatives (Fig. 27), possessing additional properties compared to regular chitosan.[286] Combining chitosan with these derivatives allows the creation of edible films, offering a wide array of distinctive applications in the realm of food packaging.[287–295]

Fig. 28 represents different methods of fabrication of chitosan-based films.

Fig. 29 represents the antimicrobial mechanism of chitosan films.[296–310]

Fig. 30 represents sensing film application as a sticker sensor for pork & fish freshness.[311]

Chitosan, a biopolymer derived from shellfish exoskeletons, has emerged as a versatile material for food packaging. Chitosan-based films offer a range of functionalities, from biodegradability to antimicrobial properties. These films can be tailored to meet specific packaging needs and contribute to sustainability on multiple fronts. Pure chitosan films exhibit biodegradability and biocompatibility, making them suitable for single-use applications. Chitosan/biopolymer-based films combine chitosan with other natural polymers, enhancing mechanical strength and barrier properties. Chitosan/protein-based films can act as carriers for bioactive compounds, enhancing food safety and quality. Inorganic materials can be incorporated into chitosan films to introduce novel functionalities like UV-blocking. The antimicrobial properties of chitosan are particularly valuable in food packaging. By reducing the growth of spoilage microorganisms, chitosan-based films extend the shelf life of packaged products. This contributes to sustainability by minimizing food waste and enhancing the efficiency of the food supply chain.

Some other important biobased polymers in food packaging applications are presented in Table 3.

3.8. Hydrogel based food packaging

Hydrogel-based food packaging is an emerging area of research, encompassing various applications such as antimicrobial activity, antioxidant properties, and coatings, all of which contribute to enhancing the shelf life and overall quality of food products.[322] Hydrogels, three-dimensional polymeric materials with the capacity to absorb and swell in fluids, owe their water-absorbing ability to the presence of hydrophilic groups like –COOH, –OH, –CONH–, –$CONH_2$, and SO_3H.[323] These hydrogels can be derived from natural or synthetic polymers, held

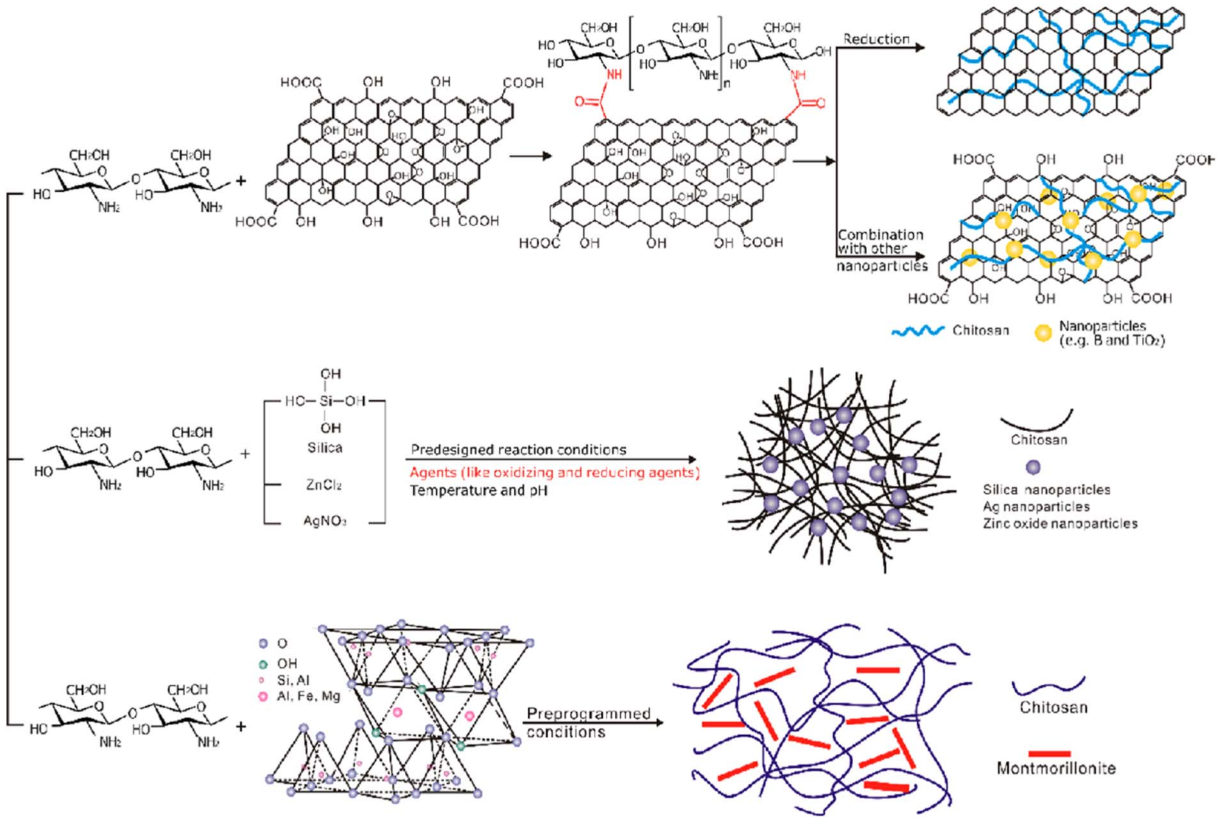

Fig. 26 Preparation of chitosan–inorganic complexes.[197] Reproduced (adapted) with permission from ref. 197. Copyright [2013] [Elsevier].

together by either physical or chemical bonds, and their 3D structure enables them to endure the pressure generated during swelling. If they can absorb fluid of over 100% of their dry weight, they are referred to as superabsorbent hydrogels.[323–325] Hydrogels can be classified based on parameters like biodegradability, crosslinking type, physical appearance, electric charge, polymer composition, responsiveness to stimuli, and more. When dissolved in solvents, they can function as colloidal gels with distinctive rheological and viscoelastic properties. Natural materials like mucilages, proteins, gums, and starch can be utilized in the formation of hydrogels, with gums and mucilages serving as protective substances produced by plants in response to environmental stress and microbial threats.[326,327] Fig. 31 illustrates the various methods of hydrogel synthesis,[328] while Fig. 32 depicts different polymerization techniques utilized in the creation of hydrogels.[329]

Some of the most important uses of hydrogels in food packaging are discussed below.

3.8.1. Absorbent pads. Hydrogels are utilized in active food packaging systems as moisture absorbents for food items with high moisture content. They are particularly suitable for products that release exudates during storage. By absorbing these exudates, hydrogel-based absorbents reduce the spoilage rate of packaged food, maintaining a low internal moisture level within the package. The effectiveness of an absorbent pad hinges on its capacity to hold exudates within its 3D structure, thereby preserving the structural integrity of the packaging and extending the shelf life of the enclosed product. Typically, an absorbent pad comprises two layers: an outer layer and an inner layer. The outer layer serves to prevent direct contact between the food and the absorbent material's inner layer. Tiny openings or holes in the outer layer facilitate the flow of exudates into the inner absorbent layer. As illustrated in Fig. 33,[324,330] the absorbent material swells upon absorption, enabling it to retain the exudate within its 3D structure.

3.8.2. Colorimetric indicator. Hydrogel-based colorimetric indicators for food packaging use water-absorbing polymeric materials combined with natural extracts to monitor food quality. Composed of ingredients like gelatin, citric acid, *N*,*N*-dimethyl acrylamide, and natural pigments such as *Basilicum* extract, these hydrogels change color in response to spoilage or contamination, providing a visual indication of food freshness. This technology enhances food safety by extending shelf life through antimicrobial and antioxidant properties, while promoting environmental sustainability as the materials are biodegradable and reduce reliance on synthetic dyes. Additionally, using natural pigments decreases health risks associated with synthetic dyes. Despite challenges in scalability, cost, regulatory approval, and maintaining stability, hydrogel-based colorimetric indicators offer a promising solution for intelligent food packaging, aligning with goals of sustainability and consumer safety.[331,332] Lu *et al.* reported a sugarcane bagasse nanocellulose-based hydrogel as a freshness indicator for chicken, as depicted in Fig. 34.[333]

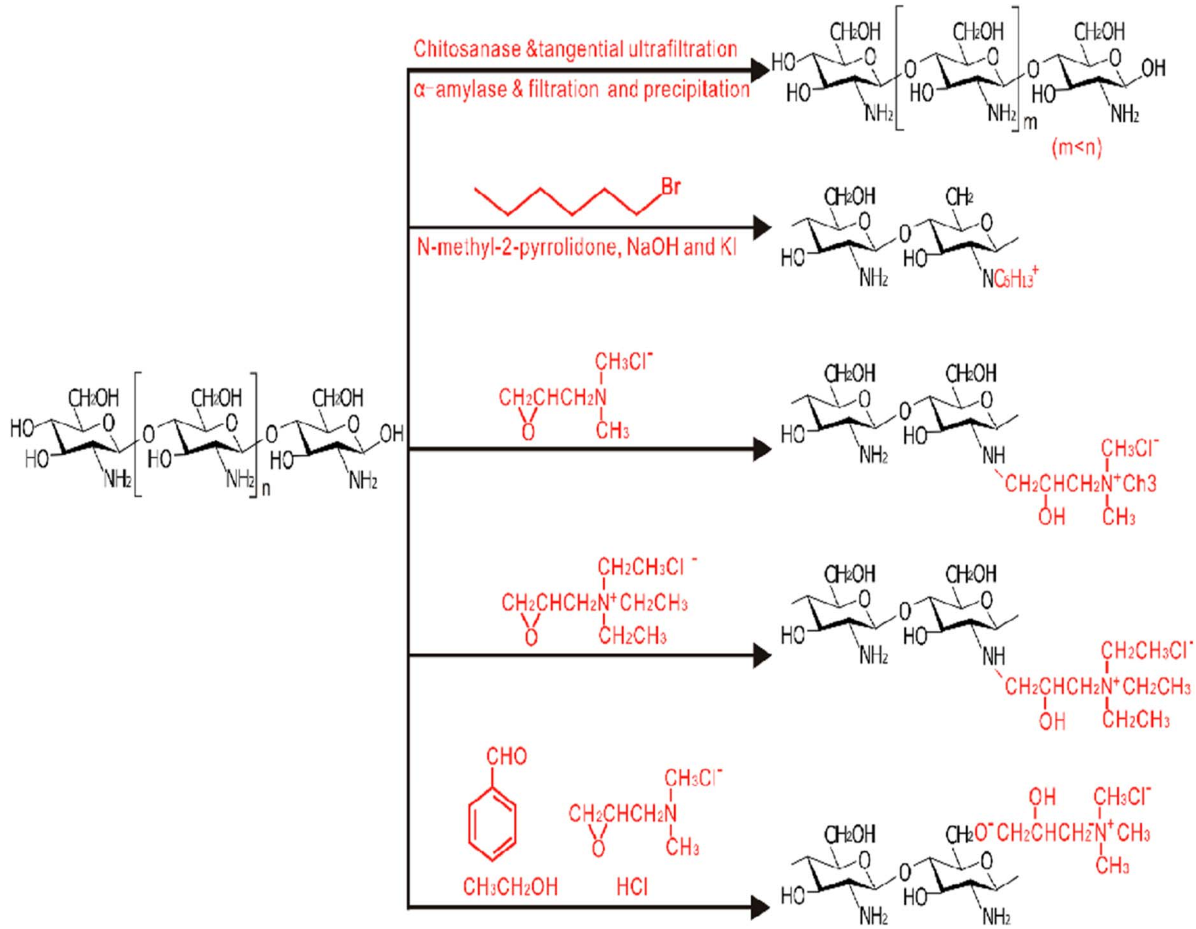

Fig. 27 Chitosan derivative development of fabrication of chitosan/chitosan derivatives-based films.[197] Reproduced (adapted) with permission from ref. 197. Copyright [2013] [Elsevier].

3.8.3. Antimicrobial property. Hydrogels, when combined with antimicrobial agents like bioactive compounds or nanoparticles, exhibit antimicrobial properties. Alpaslan investigated the efficacy of *Basilicum* extract's antimicrobial activity against *E. coli*, *B. subtilis*, and *S. aureus*, finding notable antimicrobial effectiveness.[332] Similarly, Wang and Rhim developed an agar/alginate/collagen ternary blend incorporated with grapefruit seed extract and silver nanoparticles. Their hydrogel film was tested against Listeria monocytogenes and *Escherichia coli*, demonstrating greater activity against the latter compared to the former.[324,334–336]

3.8.4. Antioxidant property. The addition of antioxidant materials to hydrogel films enhances their antioxidant properties. An instance of this is the use of ferulic acid-based antioxidant film to prevent butter oxidation.[337] Additionally, the incorporation of *Basilicum* extracts into hydrogels significantly improves their antioxidant activity.[332]

3.8.5. Biodegradable packaging. The biodegradation of some hydrogels can be done because of their biopolymeric nature as they contain bio-polysaccharides in their constituents and their structures contain glycosidic bonds degradation of which can be done by enzymatic action.[338] One of the most important and widely used biopolymers for the development of hydrogel matrices is chitosan. Important linkages which are targeted by enzymatic action include *N*-acetyl-glucosamine-*N*-acetyl-glucosamine, glucosamine–glucosamine and glucosamine-*N*-acetyl-glucosamine. The enzymes which are responsible for chitosan biodegradation include lysozyme and bacterial enzymes. The degree of deacetylation determines the extent of chitosan degradation, since low biodegradation results from a high level of deacetylation.[339]

3.8.6. Other potential applications of hydrogels in food industry. Table 4 (ref. 344) shows some other potential applications of hydrogels in the food industry.

Hydrogels, three-dimensional networks of hydrophilic polymers, have found applications in food packaging that promote sustainability. Absorbent pads made from hydrogels manage excess moisture within food packages, preventing spoilage and maintaining food quality. By controlling moisture levels, these pads minimize microbial growth and the potential for mold formation. Colorimetric indicators incorporated into hydrogels offer a visual indication of food freshness. These indicators react to specific compounds released during food spoilage, providing consumers with a simple and intuitive tool to assess food quality. This reduces unnecessary food waste and empowers consumers to make informed choices. Hydrogels can

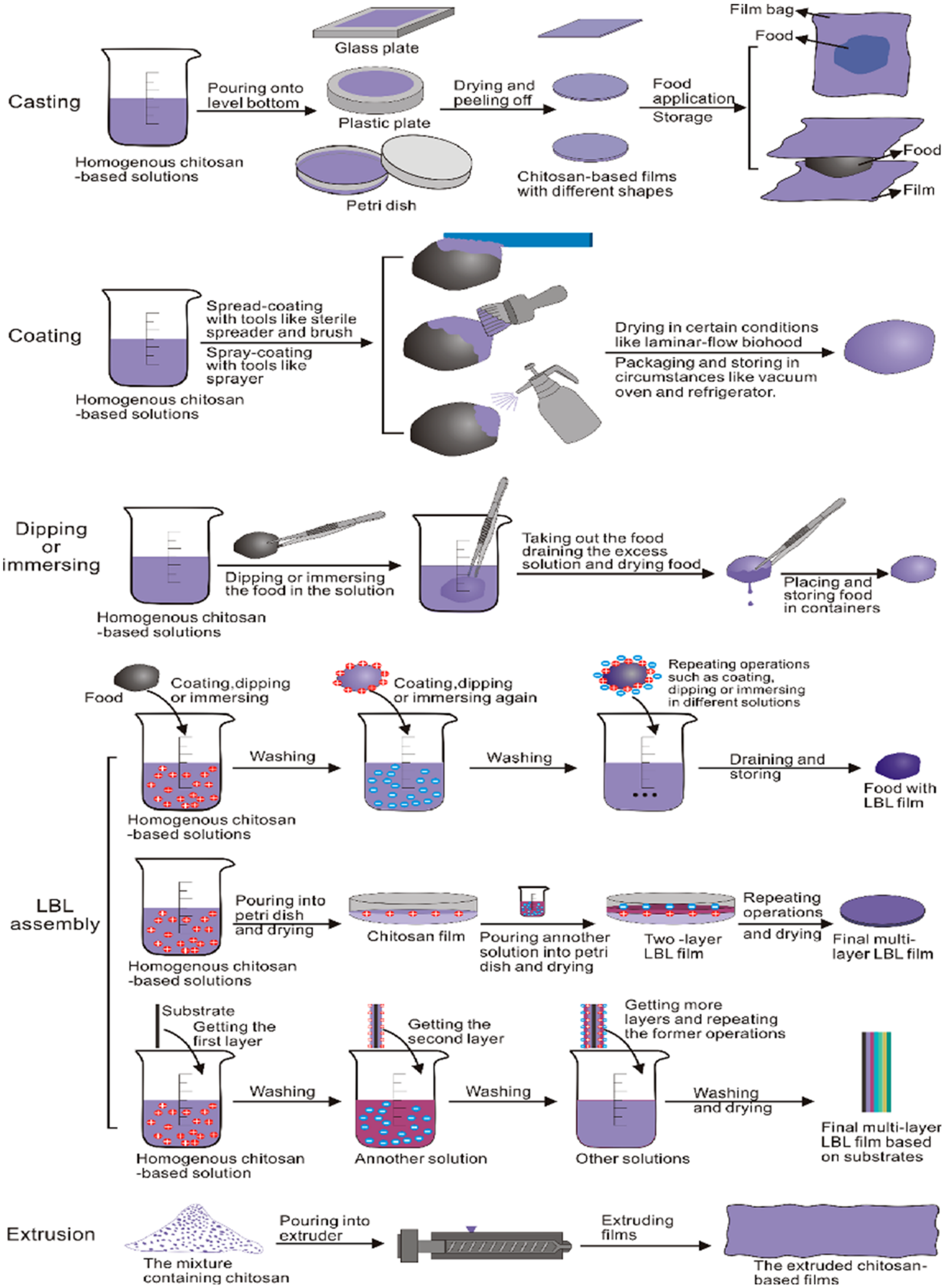

Fig. 28 Different methods of fabrication of chitosan-based films.[197] Reproduced (adapted) with permission from ref. 197. Copyright [2013] [Elsevier].

also possess antimicrobial and antioxidant properties. This contributes to food preservation by minimizing microbial growth and oxidative reactions. Additionally, the biodegradability of hydrogels aligns with sustainability goals, ensuring that packaging waste does not linger in the environment.

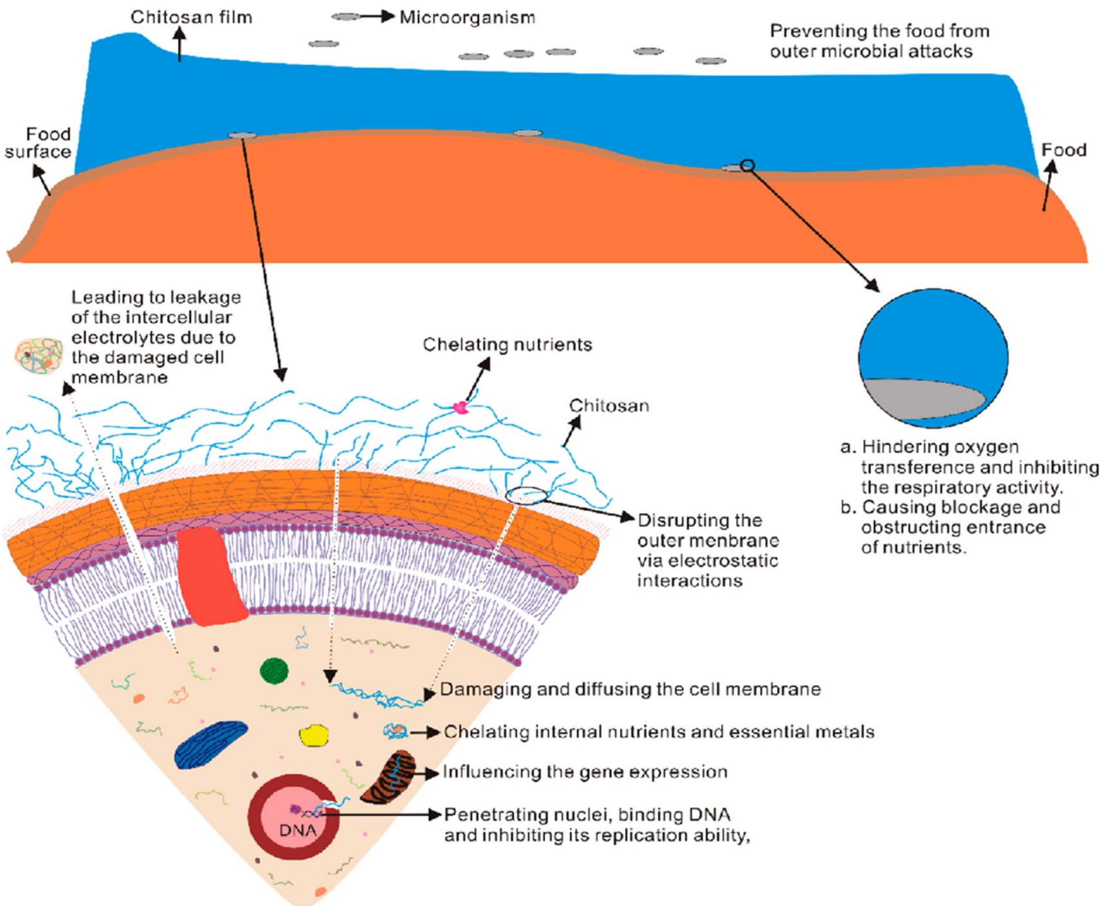

Fig. 29 Antimicrobial mechanism of chitosan films.[197] Reproduced (adapted) with permission from ref. 197. Copyright [2013] [Elsevier].

3.9. Biodegradable plastics in food packaging

Environmentally friendly biodegradable plastics make up just 1% of the yearly production and readily decompose in the environment through a fragmentation process.[345] The different stages of plastic degradation are depicted in Fig. 35,[346] while Fig. 36 illustrates the typical mechanism of plastic degradation under aerobic conditions.[347]

The factors which affect the degradation of plastics include chemical characteristics; raw ingredients used and the finished

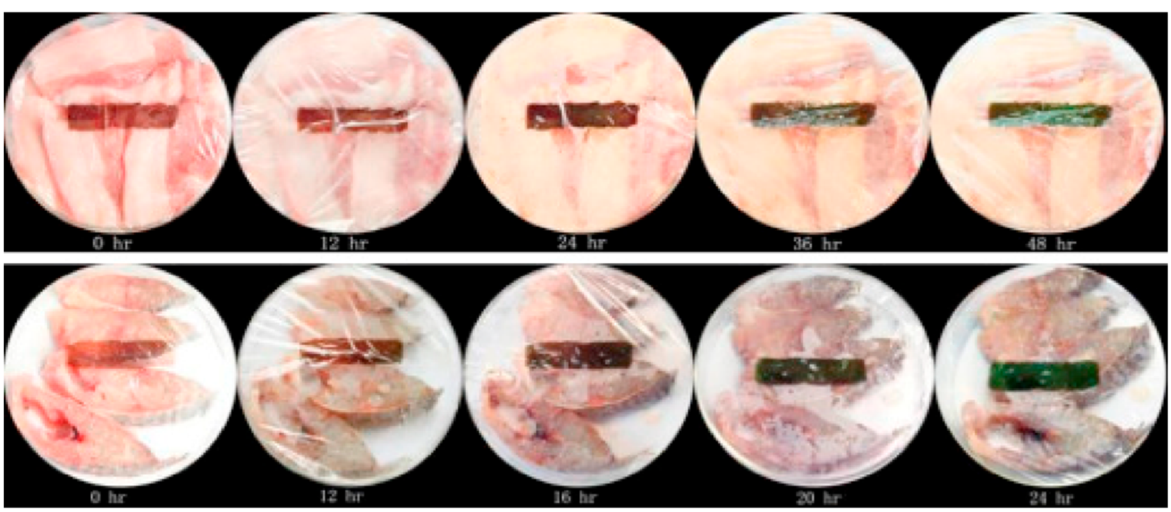

Fig. 30 Sensing film application as a sticker sensor for pork & fish freshness.[311] Reproduced (adapted) with permission from ref. 311. Copyright [2014] [Elsevier].

Table 3 Important biobased polymers in food packaging applications

Biopolymer used	Additive added	Synthesis method	Food packaged	Main characteristics	References
Polylactic acid	Nano-zinc oxide (ZnONPs), pomegranate peel extract	Solvent-casting method	Cherry tomatoes	Increased UV barrier, WVP, elongation at break, good antibacterial and antioxidant activity	312
Polylactic acid	Zein, polyethylene glycol (plasticizer)	Blended method	None used	Improved mechanical and water barrier properties	313
Polylactic acid	Cerium lactate (Ce-LA)	Precipitation method	None used	Increased crystallinity and enhanced antibacterial properties	314
Yam starch	Bentonite	Bentonite	None used	Increased tensile strength, high degradability	315
Starch-based bioplastics	2,2,6,6-Tetramethylpiperidine 1-oxy-oxidized cellulose nanofibers and zinc oxide nanoparticles	Not clearly defined (possibly gel-formation)	None used	Improved tensile strength (up to 24.54 MPa), water resistance, thermal resistance, biodegradability	316
Yam starch	Glycerol (plasticizer), citric acid	Gel formation	Fish	High tensile strength (24.60 MPa), smart pH auto color detection	317
Pectin	Spent coffee grounds extracts, PHA (coating)	Dipping method	Mashed carrot	Improved water vapor permeability	318
Alginate	Nitrogen carbon dots (NCDs), layered clay	Casting method	Banana	Improved mechanical property and reduced surface wettability	319
Protein and pectin (yellow passion fruit peel)	None mentioned	Casting method	None used	Improved strength and elasticity, improved thermal stability, low water permeability	320
Alginate	Citrus lemon extract	*In situ* method	None used	Good antibiofilm effect	321

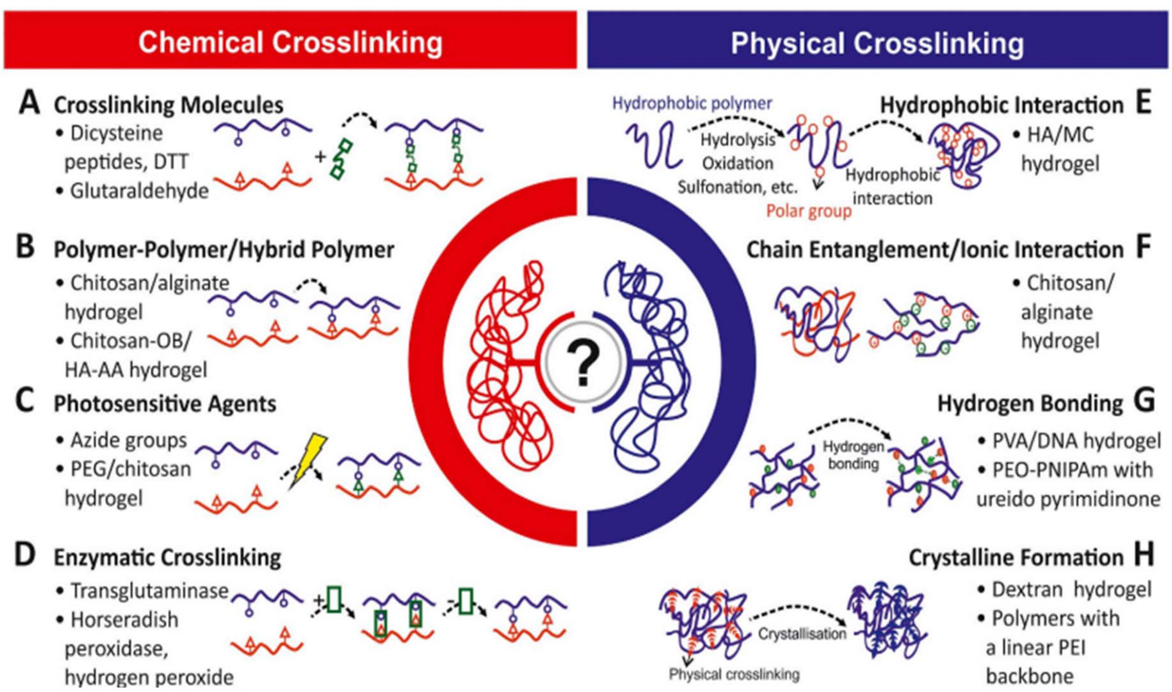

Fig. 31 Methods of hydrogel synthesis: (A) crosslinking molecules, (B) polymer–polymer/hybrid polymer, (C) photosensitive agents, (D) enzymatic crosslinking, (E) hydrophobic interaction, (F) chain entanglement/ionic interaction, (G) hydrogen bonding, and (H) crystalline formation.[328]

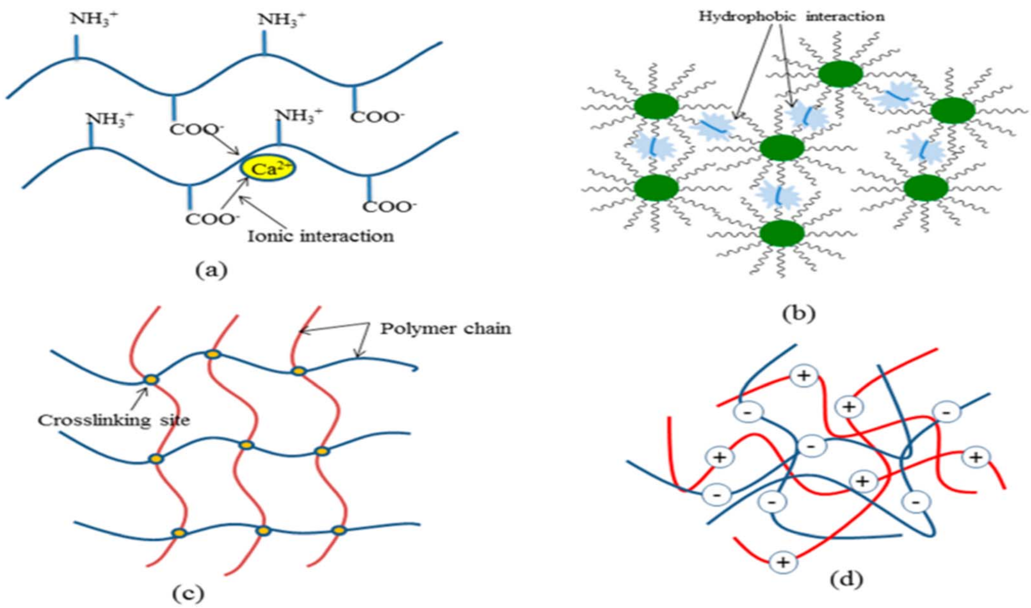

Fig. 32 Different polymerization techniques for the synthesis of hydrogels: (a) ionic interaction, (b) hydrophobic interaction, (c) cross-linking junction by cooling, and (d) complex coacervate.[329] Reproduced (adapted) with permission from ref. 329. Copyright [2018] [ACS].

product's design beside climatic conditions such as temperature and location (Fig. 37).

The determination of the biodegradability of packaging materials can rely on the following characteristics:[348]

(a) To achieve up to 90% biodegradability, the product should consist of 50% organic mass.

(b) It should not contain heavy metals beyond the permissible health limits.

(c) The CO_2 amount should allow for permeability both inside and outside the packaging material.

(d) A low oxygen permeability coefficient contributes to an increased shelf life of food.[349]

(e) It should possess high tensile strength, which can be enhanced by incorporating nanoparticles like PCL and PLA.[350]

(f) A smooth surface can be achieved by introducing biosurfactants such as polysaccharide-lipid complexes, phospholipids, and lipoproteins.[351]

(g) Additives, including colorants, agricultural waste, cellulose nanofibers, nanocomposites, dialdehyde starch, silica, edible oils, natural rubber, and soy protein, can improve biodegradability.[352,353]

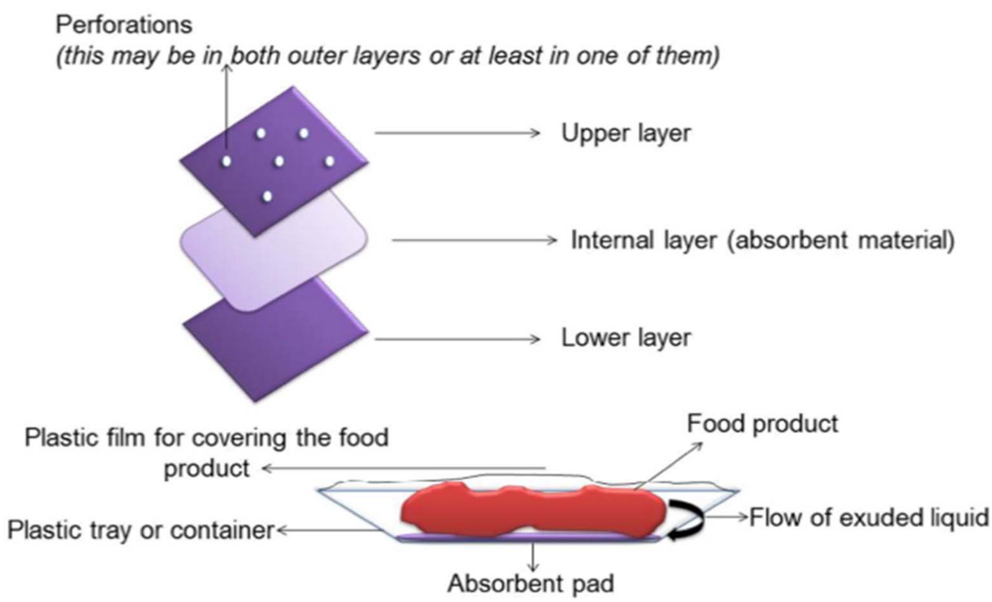

Fig. 33 Absorbent pad.[330] Reproduced (adapted) with permission from ref. 330. Copyright [2016] [Elsevier].

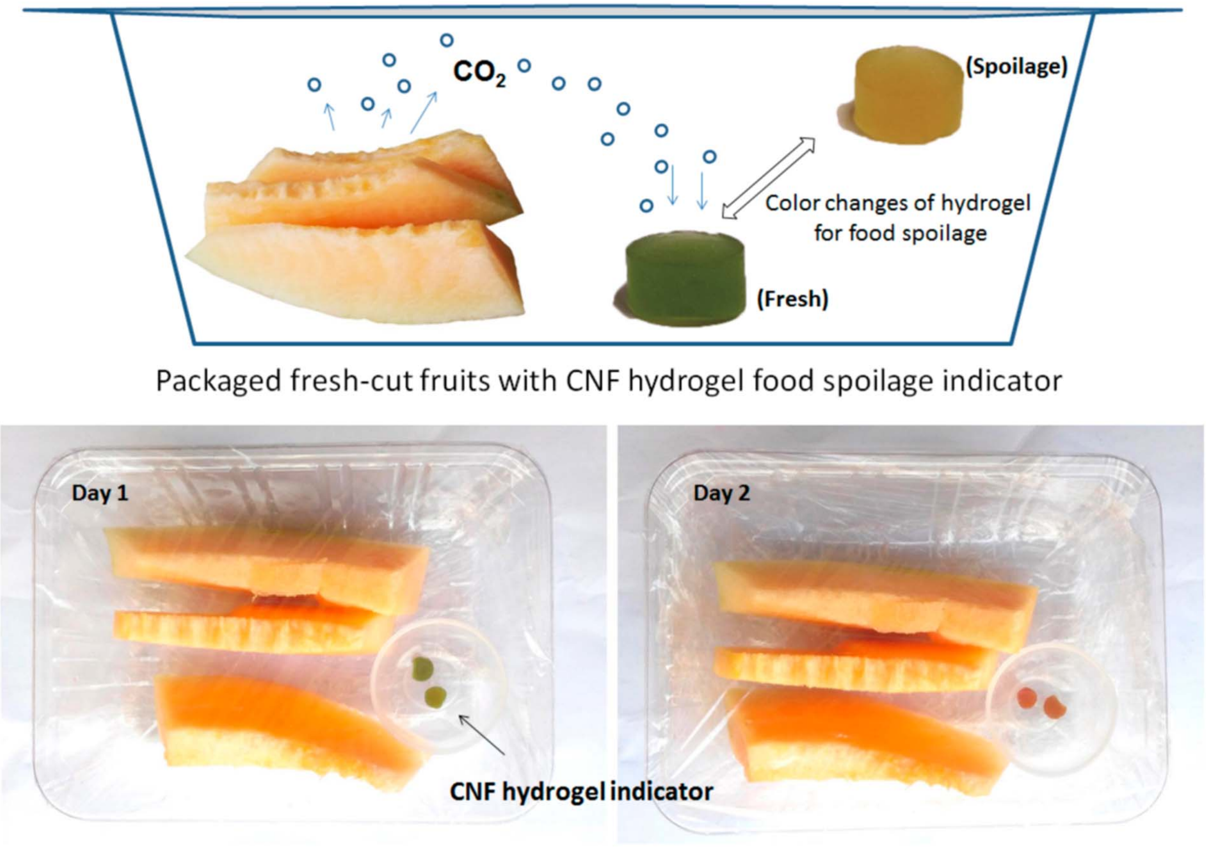

Fig. 34 Cellulose nanofibrils hydrogel.[333]

The biodegradable plastics are categorized into two groups, as illustrated in Fig. 38.[354]

Fig. 39 represents various approaches of barrier biodegradable packaging.[355]

Biodegradable plastics have become a crucial component in the food packaging sector, not only providing appealing packaging but also extending the shelf life of food products. These plastics are used in various forms of packaging, including net

Table 4 Potential applications of hydrogels in the food industry

Main goal	Main characteristic	Hydrogel composition	Reference
Food freshness indicator	Generated information regarding food freshness based on metabolites production in the food	Poly(*N*,*N*-dimethyl acrylamide-*co*-methacryloyl sulfadimethoxine) (poly(DMA-*co*-SDM)) hydrogels incorporated with methacryloyl sulfadimethoxine monomer (SDM) with a pH-responsive group	340
Stability and retention of volatiles substances	Flavor encapsulation (nanoemulsions in hydrogels)	Flavored nanoemulsions incorporated in low methoxyl (LM) pectin & whey protein isolate (WPI) at pH 4.0	341
	Controlled release occurs by pH modification	Orange oil, medium-chain triglyceride (MCT) oil, & WPI (stable nanoemulsions)	
Improvement of bioavailability of lipophilic compounds	Incorporation of lipophilic bioactive compounds (*e.g.* β-carotene) in food matrix, improving their bioavailability	Hydrogels based on polysaccharides (starch and xanthan gum) to incorporate β-carotene emulsion	342
Method for aflatoxin B1 detection	Detection of aflatoxin B1 in food sample when the hydrogel causes collapse of the network, and occurs the release of urease into the analyzed solution	DNA hydrogel	343

coverings for fruits, rigid beverage bottles, and egg trays. Different biodegradable polymers offer diverse applications in the food processing and packaging industry, with their combination often leading to material enhancement.[356] For instance, the combination of cassava starch and sugarcane bagasse, along with other polysaccharides like orange bagasse and corn husk, has demonstrated greater resistance and rigidity in trays compared to EPA trays. Similarly, a high-quality food packaging material can be achieved through the blending of PHA with PHB.[357]

Incorporating PHA/ZnO and poly(3-hydroxybutyrate-*co*-3-hydroxyvalerate) with wood fiber improves tensile strength and elasticity, resulting in the formation of a thin film suitable for packaging junk food and wrapped meals.[358] The blending of alginate and cellulose also yields notable properties and applications. In the contemporary context, biodegradable films are extensively used as substitutes for plastic (PE) in packaging materials. Additives, including enzymes facilitating the breakdown of plastic materials, are often introduced during the film formation process. These biodegradable films exhibit desirable properties that make them superior to PE films.[359] These include controlled respiration allowance, acting as effective barriers, maintaining structural integrity, and preventing and reducing microbiological spoilage. Fig. 40 provides an illustration of the polyethylene biodegradation process.[360]

3.9.1 Biodegradable *vs.* shelf-life. Finding a delicate balance between the objectives of biodegradability and

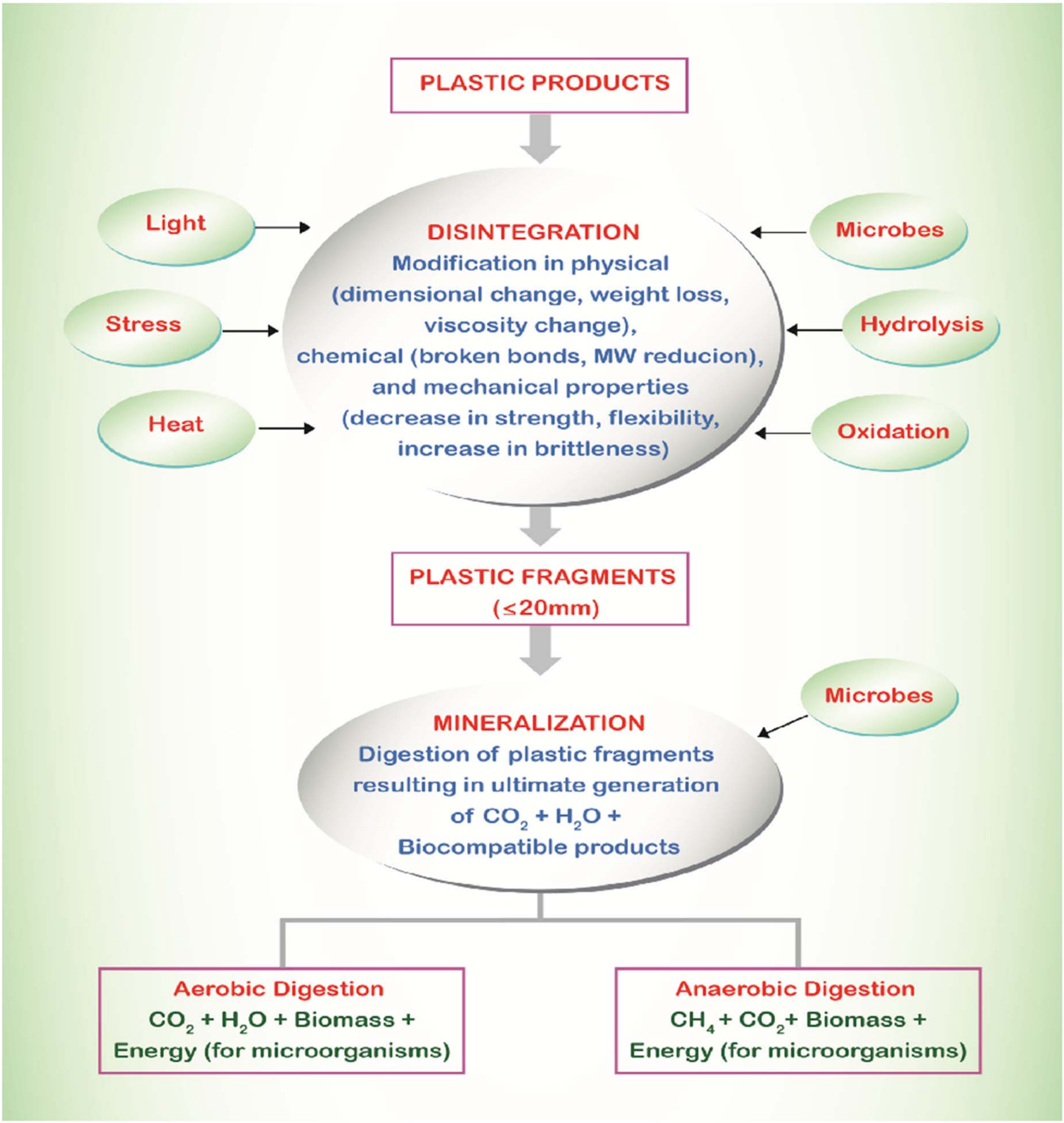

Fig. 35 Schematic representation of plastic degradation.[346] Reproduced (adapted) with permission from ref. 346. Copyright [2006] [Elsevier].

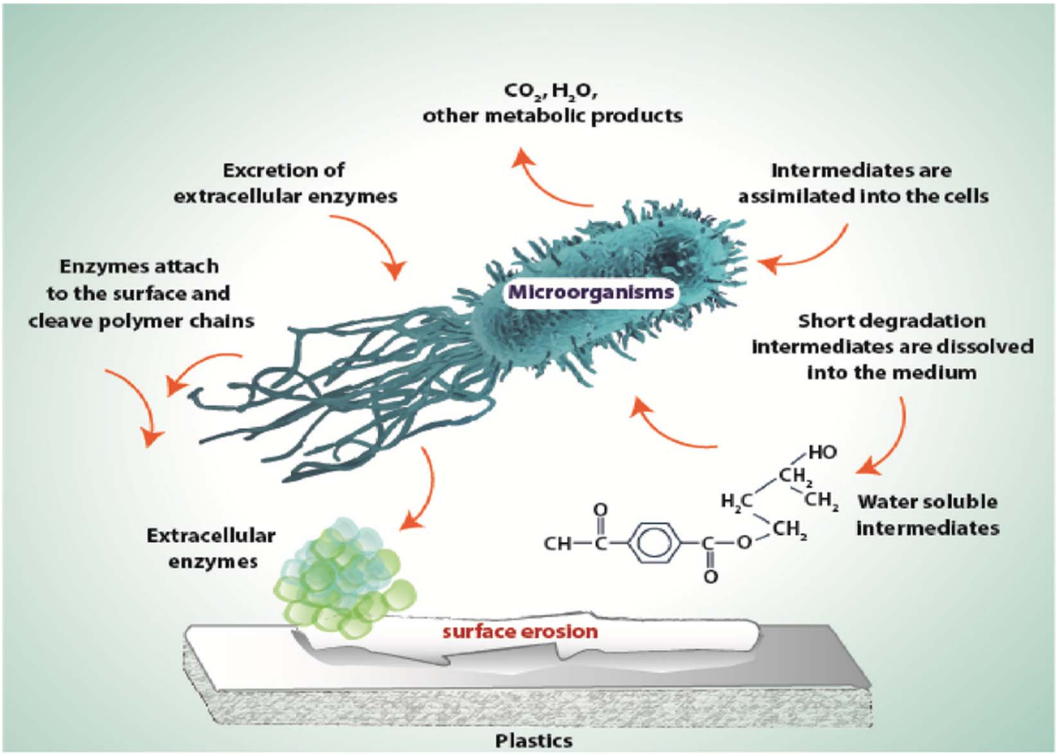

Fig. 36 General mechanism of plastic degradation under aerobic conditions.[347] Reproduced (adapted) with permission from ref. 347. Copyright [2005] [John Wiley and Sons].

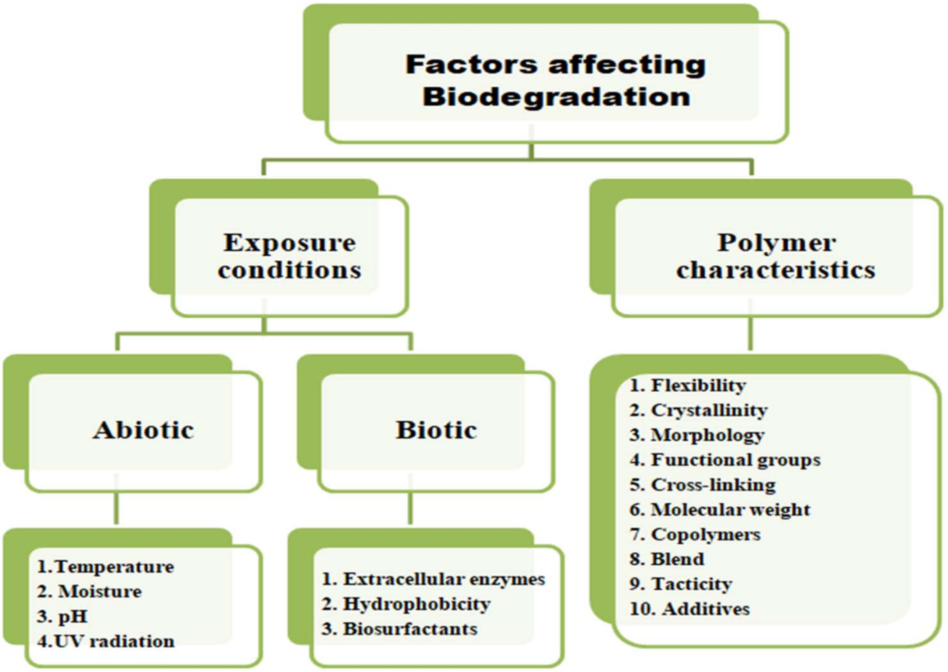

Fig. 37 Factors affecting biodegradation.

extended shelf life in food packaging poses a complex challenge. Biodegradable materials offer a promising avenue for reducing environmental impact by breaking down into harmless compounds over time, thus minimizing long-term pollution and waste accumulation. These materials typically utilize organic compounds derived from renewable sources

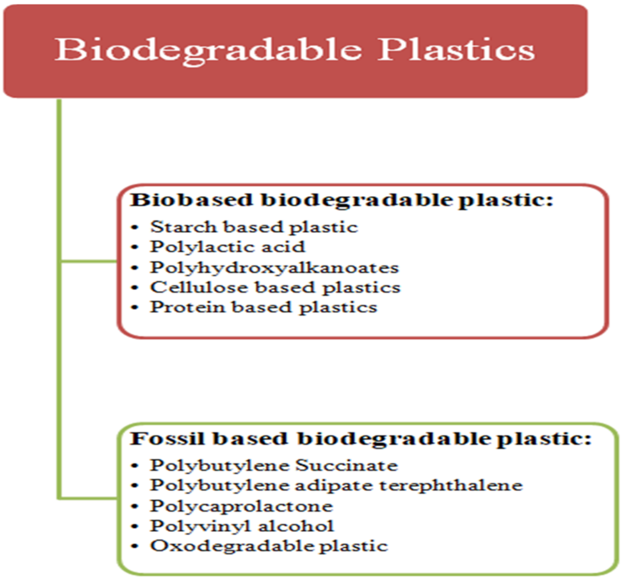

Fig. 38 Classification of biodegradable plastics.

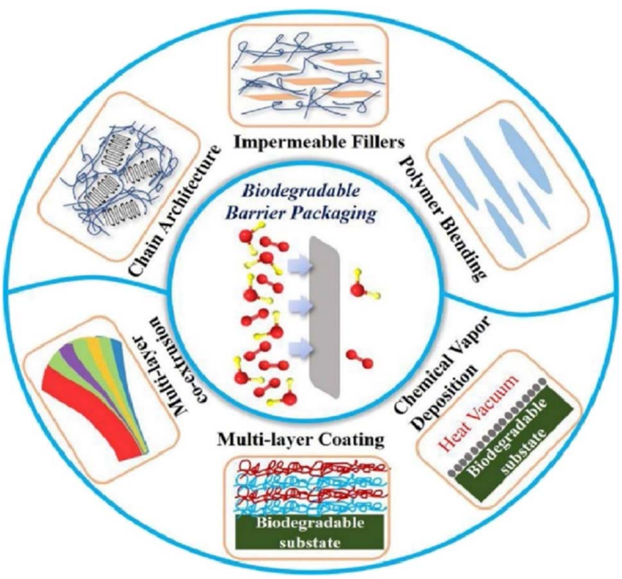

Fig. 39 High barrier biodegradable packaging approaches.[355] Reproduced (adapted) with permission from ref. 355. Copyright [2021] [Elsevier].

such as plant-based polymers or bioplastics, which decompose naturally through biological processes. However, the inherent properties of biodegradable materials often result in a trade-off with shelf life. Due to their susceptibility to degradation, biodegradable packaging may have a shorter lifespan compared to conventional packaging materials. This limitation raises concerns about the potential for premature product spoilage and increased food waste if items deteriorate before reaching consumers.

Conversely, packaging materials engineered for extended shelf life prioritize food preservation and longevity, aiming to minimize spoilage and maximize product freshness. These materials often incorporate synthetic polymers or additives that provide barriers against moisture, oxygen, and microbial contamination, thereby prolonging the shelf life of packaged goods. While effective in preserving food quality and reducing waste at the consumer level, these materials present challenges in terms of environmental sustainability. Their resistance to degradation means they persist in the environment long after their intended use, contributing to pollution, litter, and ecosystem harm.

Achieving a harmonious convergence between biodegradability and extended shelf life requires innovative strategies that reconcile conflicting priorities. This could involve the development of biodegradable materials with enhanced durability and protective properties, effectively extending their useful lifespan without compromising their ability to break down naturally. Alternatively, integrating shelf-life-extending technologies, such as modified atmosphere packaging or active packaging systems, into biodegradable materials may offer a viable solution by preserving product freshness while still allowing for eventual decomposition.

Furthermore, comprehensive life cycle assessments are essential for evaluating the environmental impacts of different packaging options holistically. These assessments consider not only the end-of-life disposal of packaging but also the energy consumption, resource use, and emissions associated with manufacturing, transportation, and usage stages. By adopting a holistic approach that considers the entire life cycle of packaging materials, including their biodegradability, shelf life, and environmental footprint, stakeholders can make informed decisions that promote both sustainability and food safety. Ultimately, striking a balance between biodegradability and shelf life requires careful consideration of diverse factors, including consumer preferences, regulatory requirements, technological advancements, and environmental stewardship goals.[361]

The proliferation of plastic waste has sparked interest in biodegradable plastics as a sustainable alternative. Biodegradable plastics are derived from renewable resources like cornstarch or sugarcane. They are designed to break down more readily in the environment, reducing the persistence of plastic waste. By transitioning from conventional plastics to biodegradable alternatives, the packaging industry addresses the issue of plastic pollution. Biodegradable plastics can be composted alongside organic waste, minimizing the load on landfills and contributing to a circular economy.

3.10. Essential oil-based pickering emulsions for food packaging

Essential oils, characterized by their low molecular weight, high volatility, and lipophilic nature, constitute a fraction of materials with varying components depending on factors such as climate, growth stage, plant material, harvest, and health, among others. These components can undergo interconversion through dehydrogenation, oxidation, isomerization, and cyclization triggered chemically or enzymatically.[362] Vegetable or

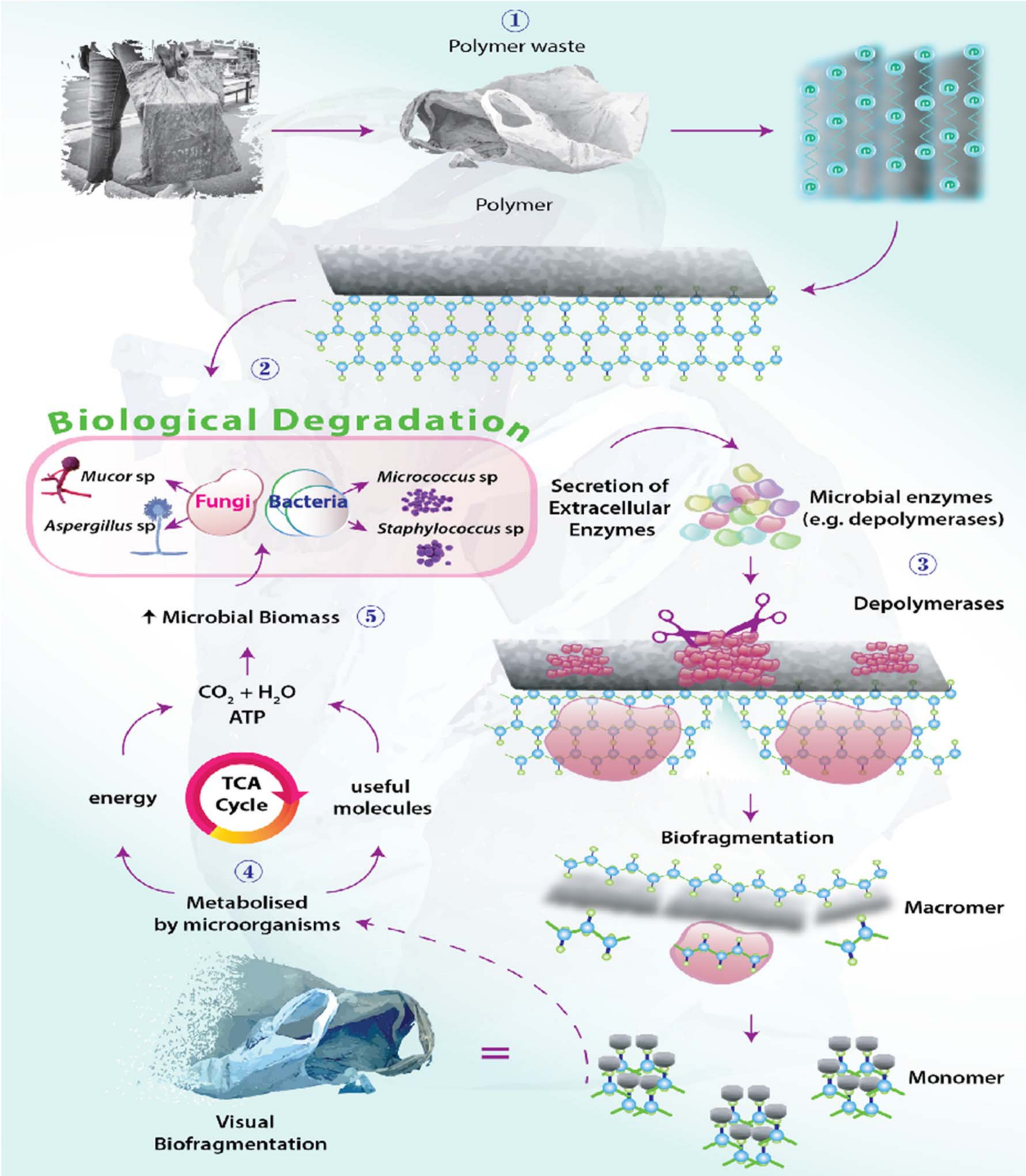

Fig. 40 Biodegradation of polyethylene.[360] Reproduced (adapted) with permission from ref. 360. Copyright [2021] [Elsevier].

edible oils primarily consist of triacylglycerides (96%), alongside antioxidants, free fatty acids, tocopherols, phospholipids, waxes, and phytosterols.[363] Owing to their diverse bioactive composition, essential oils find extensive use in food systems. They contribute to the enhancement of food quality and the reduction of food shelf life resulting from microbial contamination and lipid oxidation processes. Utilizing essential oils from cinnamon, cloves, thyme, rosemary, and oregano has been effective in extending the shelf life of various food products, including vegetables, meat, and fish.[364]

However, the direct application of essential oils in food is restricted due to their intense flavor and high volatility. To expand their usage in food products, these limitations can be overcome through the development of Pickering Emulsions (PEs) based on various essential oils using different Pickering particles. Notably, PE formulations of marjoram oil, clove, tea tree oil, cinnamon, cardamom, oregano, peppermint oil, rosemary oil, and cedarwood are extensively discussed, as summarized in Table 5.[373]

Fig. 41 illustrates the incorporation of gelatin/agar-based films with Pickering emulsion[374] and SSOS-based Pickering

Table 5 Essential oil-based Pickering emulsions in food packaging

Essential oil	Pickering particle	Fabrication method	Applications	Reference
Cinnamon	Zein–pectin composite nanoparticles	High speed homogenization	Antimicrobial agent in apple slices	365
Cinnamon oil & corn oil	Sodium starch octenyl succinate (SSOS)	Homogenization	Active biodegradable films with improved antimicrobial & antioxidant activities	366
Marjoram	Whey protein isolate (WPI)/inulin	Ultrasonication	Active pectin film as a new active packaging system	367
Clove	Zein colloidal particles	High speed homogenization and ultrasonication	Chitosan based edible film with antimicrobial properties	368
Clove	Cellulose nanofiber (CNF)	High speed homogenization	Gelatin/agar active film with improved antioxidant activity and their application as active food packaging	369
Peppermint	Chitosan decorated silica nanoparticles	Homogenization	PE based composite microcapsules using HPMC which is a promising strategy for antibacterial applications	370
Oregano	Zein–pectin nanoparticle	High speed homogenization	Strawberries preserved in konjac glucomannan active packaging films	371
Oregano	ZnO nanoparticle	High-shear homogenization	Cellulose nanofibril film with antioxidant & antimicrobial activity	372

emulsion films infused with cinnamon essential oil.[375] Additionally, Fig. 42 represents the depiction of oregano essential oil Pickering emulsion stabilized by CNCs[376] and the formation of peppermint oil-loaded composite microcapsule based on chitosan-decorated silica nanoparticle stabilized Pickering emulsion templating.[370]

In nutshell, the non-toxic and biodegradable nature of essential oil based Pickering emulsions and their fabrication by using natural Pickering particles made them suitable to be used in biomedicine, food, cosmetics, *etc.* applications. Their applications in the food industry include as preservative, antimicrobial and antioxidant agent. Conventional packaging materials are non-biodegradable and for overcoming this issue, EO-loaded PE are incorporated into biodegradable packaging films for the generation of active and edible films. Such films are found to be used widely in food packaging for the improvement of shelf life of food and other similar applications some of them still need to be explored further.[373,377]

Pickering emulsions, stabilized by solid particles, offer a novel avenue for sustainable food packaging. Essential oil-based Pickering emulsions combine the antimicrobial properties of essential oils with stable emulsions, reducing the need for synthetic emulsifiers. These emulsions can be applied as coatings to packaging materials, providing antimicrobial protection to packaged foods. By incorporating essential oils into packaging, manufacturers can minimize the need for synthetic antimicrobial agents. This aligns with sustainability goals by utilizing natural compounds to enhance food safety and quality. Additionally, Pickering emulsions promote efficient resource utilization by providing a stable platform for essential oil delivery.

4. Greener fabrication processes, underlying toxicity, environmental ramifications and techno-economic assessments of sustainable food packaging materials

4.1. Greener processes in fabrication

Adopting greener processes in the fabrication of sustainable food packaging materials is a pivotal step towards reducing the environmental impact of packaging production. Traditional manufacturing methods often rely heavily on fossil fuels and energy-intensive processes, leading to significant greenhouse gas emissions and resource depletion. To address this, companies are increasingly turning to eco-friendly practices.

One key aspect is the integration of renewable energy sources into manufacturing facilities. Solar panels and wind turbines can provide a substantial portion of the energy required for production, drastically reducing reliance on non-renewable sources. Additionally, optimizing manufacturing processes for efficiency can significantly cut down on energy consumption. Techniques such as lean manufacturing and advanced automation minimize waste, energy use, and carbon emissions.

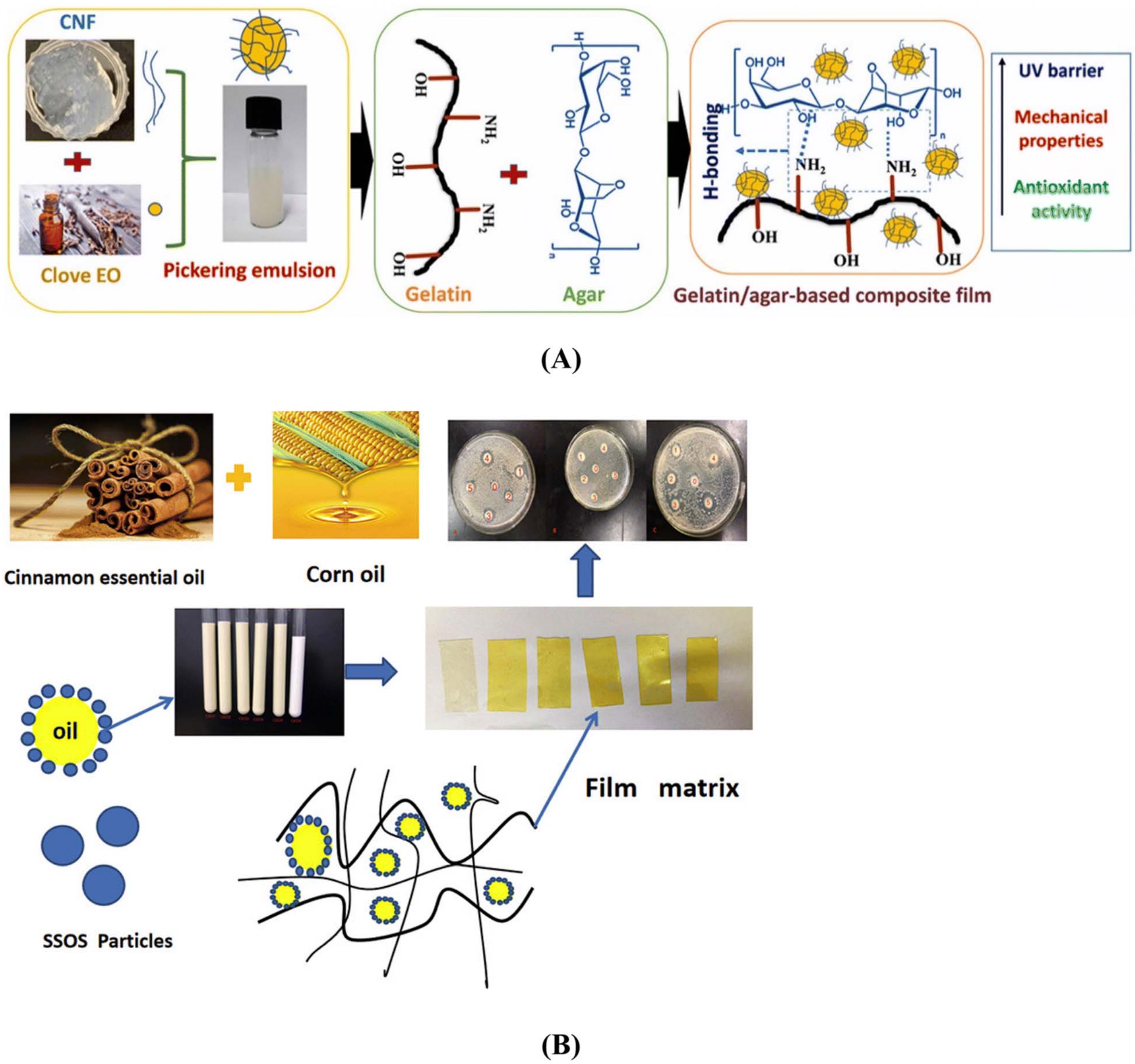

Fig. 41 (A) Pickering emulsion added gelatin/agar-based films,[374] reproduced (adapted) with permission from ref. 374. Copyright [2021] [Elsevier], & (B) SSOS-based Pickering emulsion films incorporated with cinnamon essential oil.[375] Reproduced (adapted) with permission from ref. 375. Copyright [2020] [Elsevier].

Circular economy principles also play a vital role in greener fabrication. Closed-loop systems that encourage the recycling and repurposing of materials within the production process help minimize waste generation. This approach reduces the need for virgin resources and lowers the overall environmental impact. Byproducts and waste streams from one process can be used as inputs for another, creating a more sustainable and interconnected production ecosystem.[378]

4.2. Underlying toxicity

The consideration of toxicity in sustainable food packaging materials is paramount to ensure both consumer safety and environmental well-being. Some conventional packaging materials contain additives or chemicals that can leach into food products, potentially causing health concerns for consumers. These substances can also pose a threat to the environment when they are released into ecosystems. To address this, manufacturers are increasingly adopting materials that have been rigorously tested and approved for food contact. Materials such as food-grade stainless steel, glass, and certain types of plastics undergo extensive assessments to ensure they do not release harmful substances. This not only protects consumers but also prevents contamination of the food supply chain. Furthermore, advancements in material science have led to the development of biodegradable and compostable packaging materials. These materials break down naturally over time, reducing the accumulation of non-biodegradable waste in landfills and oceans. However, it's important to conduct thorough testing to ensure that these materials break down safely without releasing harmful compounds.[379]

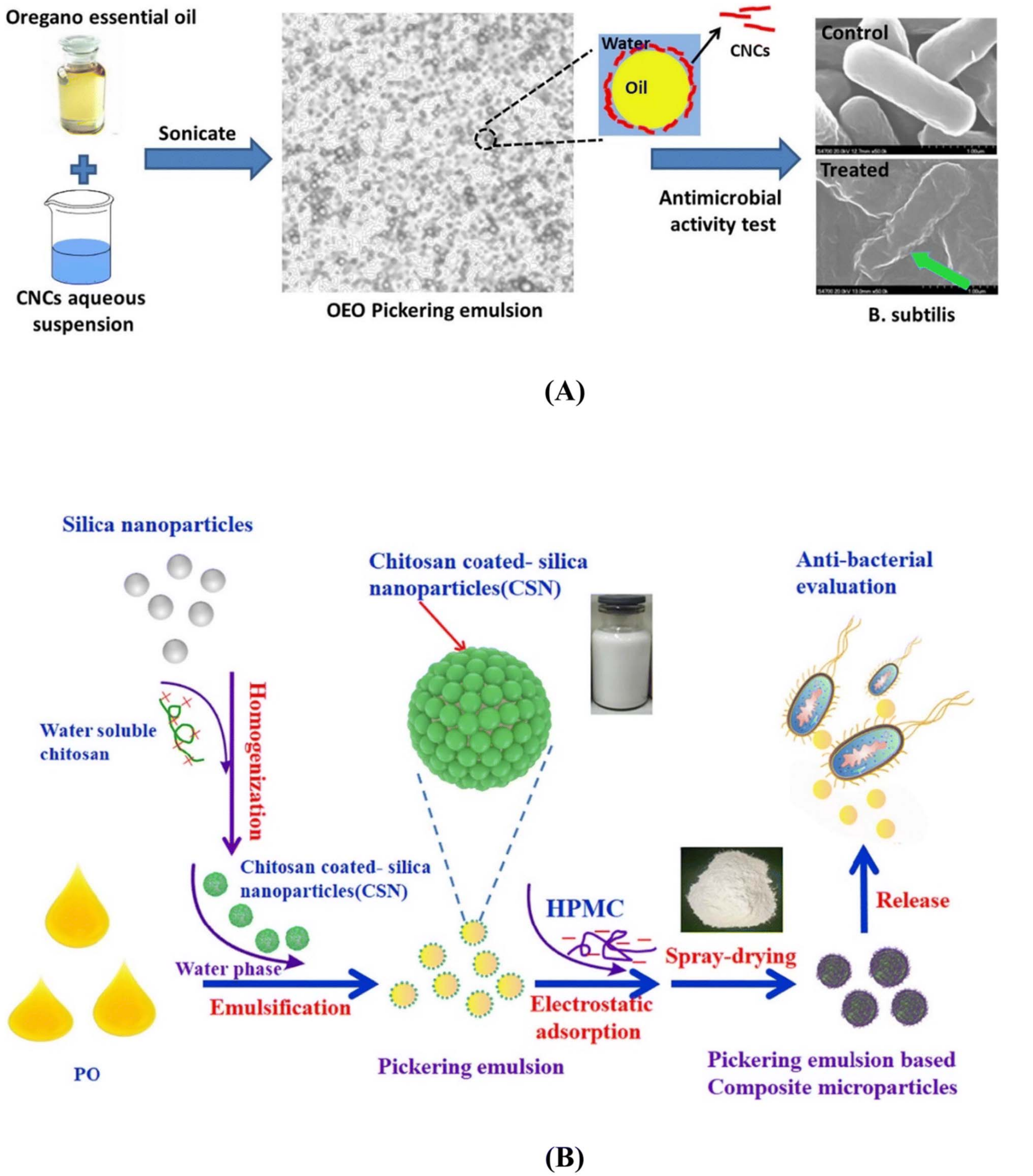

Fig. 42 Schematic representation of (A) oregano essential oil Pickering emulsion stabilized by CNCs,[376] reproduced (adapted) with permission from ref. 376. Copyright [2018] [Elsevier], & (B) peppermint oil-loaded composite microcapsule based on chitosan-decorated silica nanoparticle stabilized Pickering emulsion templating.[370] Reproduced (adapted) with permission from ref. 370. Copyright [2021] [Elsevier].

4.3. Environmental ramifications

Evaluating the environmental ramifications of packaging materials goes beyond their immediate impact and considers their lifecycle effects. Traditional packaging materials often contribute to carbon emissions, deforestation, and habitat destruction. Sustainable alternatives aim to mitigate these issues. One key consideration is the carbon footprint of packaging materials. Materials that require significant energy for extraction, production, and transportation contribute more to climate change. Sustainable options, such as plant-based bioplastics or recycled materials, often have a lower carbon footprint. Additionally, sustainable materials like bamboo and jute grow rapidly and require fewer resources compared to traditional materials like wood or cotton. Biodiversity is another critical concern. Unsustainable packaging materials, particularly those derived from resource-intensive processes, can contribute to habitat loss and disruption of ecosystems. Choosing materials that have minimal impact on biodiversity helps preserve fragile ecosystems and maintain ecological balance.[380]

4.4. Techno-economic assessments

Techno-economic assessments provide a comprehensive understanding of the financial and practical feasibility of sustainable food packaging materials. Businesses need to consider not only the initial costs of production but also the long-term benefits and potential risks. Incorporating the entire lifecycle of the packaging material is crucial. This includes evaluating the costs associated with raw material extraction, manufacturing, transportation, use, and end-of-life disposal. While some sustainable materials may have higher upfront costs, they could lead to significant savings over time due to reduced energy consumption, waste management, and potential regulatory compliance. Anticipating regulatory changes is also vital. As governments and organizations increasingly prioritize sustainability, regulations surrounding packaging materials may evolve. Materials that align with these changing regulations will be more future-proof and less likely to incur unforeseen compliance costs.[381]

In nutshell, each of these factors—greener fabrication processes, underlying toxicity, environmental ramifications, and techno-economic assessments—plays a pivotal role in shaping the landscape of sustainable food packaging materials. A holistic approach that considers these facets ensures that packaging choices are not only environmentally responsible but also economically viable and safe for consumers. As technology and awareness continue to advance, the potential for even more innovative and sustainable packaging solutions is promising.

5. Applications of chemical methods/chemistry in the improvement of packaging properties of materials

Chemical methods play a vital role in improving the properties of food packaging materials, enhancing their performance, and addressing specific requirements of the food industry. These methods aim to modify the chemical composition or structure of packaging materials to achieve desired characteristics. Here are some common chemical methods used for improving the properties of food packaging.

5.1. Crosslinking

Crosslinking involves chemically linking polymer chains to increase the strength, durability, and thermal stability of the packaging material. Crosslinked polymers exhibit enhanced mechanical properties, better resistance to chemical degradation, and reduced gas permeability. This method is commonly used for polyethylene (PE) and polypropylene (PP) materials in food packaging.

5.2. Polymer blending

By blending different polymers, food packaging materials can benefit from a combination of desirable properties. For example, blending polyethylene with ethylene-vinyl alcohol (EVOH) can improve the gas barrier properties of the packaging, making it suitable for oxygen-sensitive food products.

5.3. Coating and lamination

Chemical coatings or laminations are applied to the surface of food packaging materials to modify their properties. Coatings can improve barrier properties, enhance printability, and add heat sealability. Lamination involves bonding multiple layers to create a composite material with specific functionalities.

5.4. Barrier coatings

Barrier coatings are applied to packaging materials to enhance their resistance to moisture, gases, and aroma migration. These coatings may include nanocomposites, metal oxides, or silicones, depending on the specific requirements.

5.5. Antimicrobial coatings

To prevent microbial growth and food spoilage, antimicrobial coatings can be applied to food packaging materials. These coatings incorporate agents like silver nanoparticles or natural antimicrobial compounds to inhibit the growth of bacteria and fungi.

5.6. Active packaging

Active packaging involves incorporating specific additives or compounds into the packaging material that interact with the food product to extend its shelf life or improve quality. For example, oxygen scavengers can be added to absorb oxygen, preventing oxidative degradation of food.

5.7. Nanotechnology

Nanotechnology offers innovative approaches to modify food packaging materials at the nanoscale level. Nanocomposites, nanolayers, or nanoparticles can be incorporated into packaging materials to improve mechanical strength, gas barrier properties, and UV resistance.

5.8. Biodegradable additives

To enhance the biodegradability of traditional plastics, biodegradable additives can be incorporated during polymerization. These additives allow the packaging material to break down more efficiently in the environment after disposal.

5.9. UV stabilization

UV stabilizers can be added to packaging materials to protect them from degradation caused by exposure to ultraviolet (UV) radiation. This is especially important for packaging materials used for products intended for outdoor storage or display.

The selection of appropriate chemical methods depends on the specific requirements of the food product, the packaging application, and the desired properties. It is essential to consider food safety regulations and ensure that the chemical modifications do not introduce any harmful substances into the food. Proper testing and evaluation are necessary to ensure the performance and safety of chemically improved food packaging materials.[382]

6. Recent advances in sustainable food packaging materials

6.1. Hybrid nanoparticle-based biopolymer electrospin coating for intelligent food packaging and shelf-life improvement of chapattis

Pomegranate peel has a great potential to act as a valuable source of antioxidants and bioactive compounds. It highlights various studies that have explored its beneficial properties, including its antioxidant, anticarcinogenic, antibacterial, antifungal, and anti-inflammatory activities. Researchers have investigated the use of pomegranate peel extracts in food packaging to improve shelf life and inhibit microbial growth. Nanoparticles, when combined with biopolymers in packaging materials, can enhance their properties, although research in this area is limited. Consequently, a study was conducted to develop biodegradable food packaging using a mixture of TiO_2, ZnO nanoparticles, and pomegranate peel powder. The coated packaging was evaluated for its ability to preserve cooked food, employing various chemical tests to assess shelf life, oxidation kinetics, and microbial activity. The results suggest that the active mixture significantly improves the shelf life of food items, indicating its potential for enhancing food packaging efficiency (Fig. 43).[383]

6.2. Glycerol-added chitosan films for food packaging

Chitosan, derived from chitin found in crustaceans and fungi, is a versatile polymer with various applications due to its unique properties such as being nontoxic, biodegradable, and antimicrobial. It is utilized in biomedical products, wound dressings, cosmetics, water treatment, fertilizers, and animal husbandry. In the food industry, it serves as a packaging material or coating to enhance the shelf life of products. To improve the mechanical properties of chitosan films, plasticizers like glycerol are often added. Glycerol, in particular, significantly enhances the flexibility and strength of these films, which is crucial for maintaining product quality during storage and transportation. However, while the effects of plasticizers on tensile and tear strengths have been studied, little attention has been paid to their impact on burst strength. This study focuses on investigating the influence of glycerol as a plasticizer on the mechanical, chemical, morphological, optical, and thermal properties of chitosan films. The research includes characterizing the glass transition temperature, transparency, Young's modulus, elongation, tensile strength, and burst strength of the films. The findings demonstrate the significant role of glycerol in enhancing various properties of chitosan films, making them suitable for food packaging applications (Fig. 44).[384]

6.3. Allicin-loaded electrospun PVP/PVB nanofibrous films with superior water absorption and water stability for antimicrobial food packaging

Poly(vinyl pyrrolidone) (PVP) is widely used in food packaging due to its excellent spinnability and safety. However, its high hydrophilicity and water solubility limit its application in packaging high-moisture food items. Cross-linking is a common method to address this issue, but many cross-linking agents pose safety concerns. Genipin, a safer alternative, is expensive. To make PVP more suitable for food packaging, researchers explored blending it with the safe and cost-effective polymer PVB. In this study, PVP/PVB-allicin (PB64-A) nanofibrous films were produced *via* electrospinning, with allicin incorporated as an antibacterial agent. PVB, known for its hydrophobic nature and biocompatibility, was blended with PVP to enhance water stability. The antibacterial efficacy of PB64-A films against *E. coli* and *S. aureus* was assessed, and their potential as antimicrobial food packaging for chicken breast was evaluated. This approach offers a safe and economical method to improve the water stability of PVP nanofibrous films for food packaging applications (Fig. 45).[385]

6.4. Poly(vinyl chloride) derived food packaging materials with antioxidative and anticancer properties

Autoxidation, a natural process involving unsaturated fatty acids and oxygen, leads to spoilage through the formation of reactive radicals and peroxides. Oxygen in the headspace of plastic bottles can initiate autoxidation, deteriorating cooking oils even before use. Adding UV radiation barrier compounds to packaging materials reduces the rate of autoxidation by limiting UV light penetration. Various natural compounds, such as tannic acid and catechin, have been identified as effective in reducing autoxidation. Vanillic acid, caffeic acid, coumaric acid, naringin, and cinnamic acid, among others, exhibit antioxidant and antimicrobial properties, contributing to health benefits and food preservation. In previous studies, novel derivatives of PVC and chlorinated polypropylene were synthesized using natural compounds for active food packaging applications. In this study, PVC derivatives functionalized with vanillic, caffeic, coumaric, and cinnamic acids, along with naringin, were synthesized and characterized. The inhibitory effects of these polymers on the autoxidation of linseed oil were investigated, highlighting their potential as antioxidants and anticarcinogens (Fig. 46).[386]

6.5. Multifunctional bionanocomposite films based on chitosan/polyvinyl alcohol with ZnO NPs and *Carissa carandas* extract anthocyanin for smart packaging materials

Polyvinyl alcohol (PVA) is a synthetic polymer known for its biodegradability, water solubility, and compatibility. It is widely used in food packaging due to its transparent, odorless, and adhesive nature. Blending PVA with chitosan (CS) forms

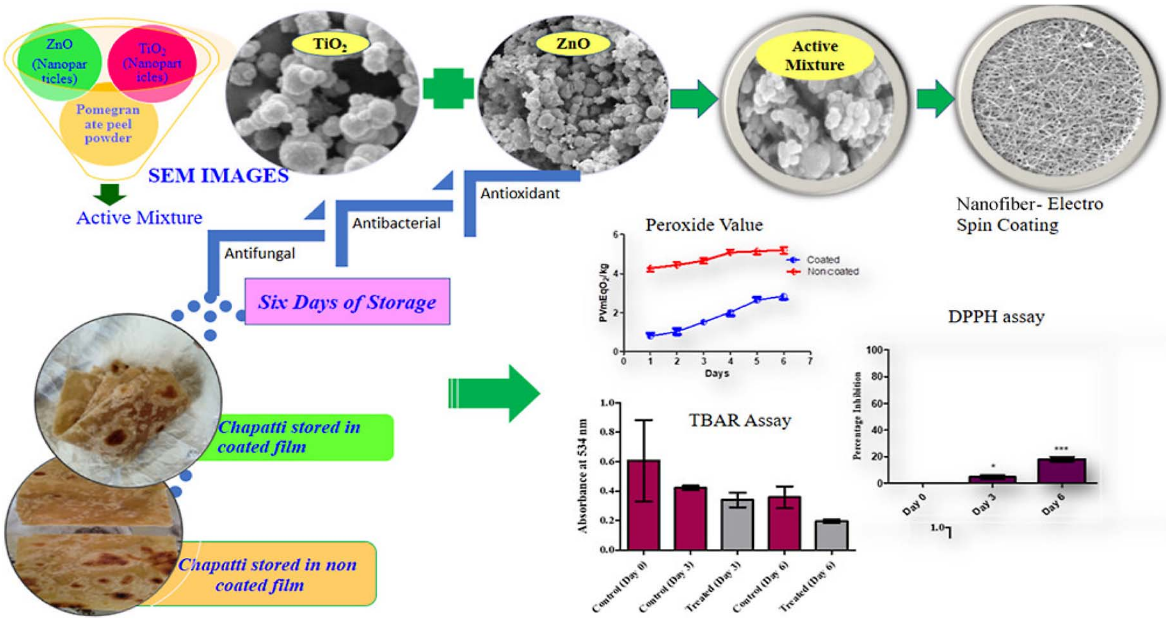

Fig. 43 Schematic representation of hybrid nanoparticle-based biopolymer electrospin coating for intelligent food packaging and shelf-life improvement of chapattis.[383] Reproduced (adapted) with permission from ref. 383. Copyright [2023] [ACS].

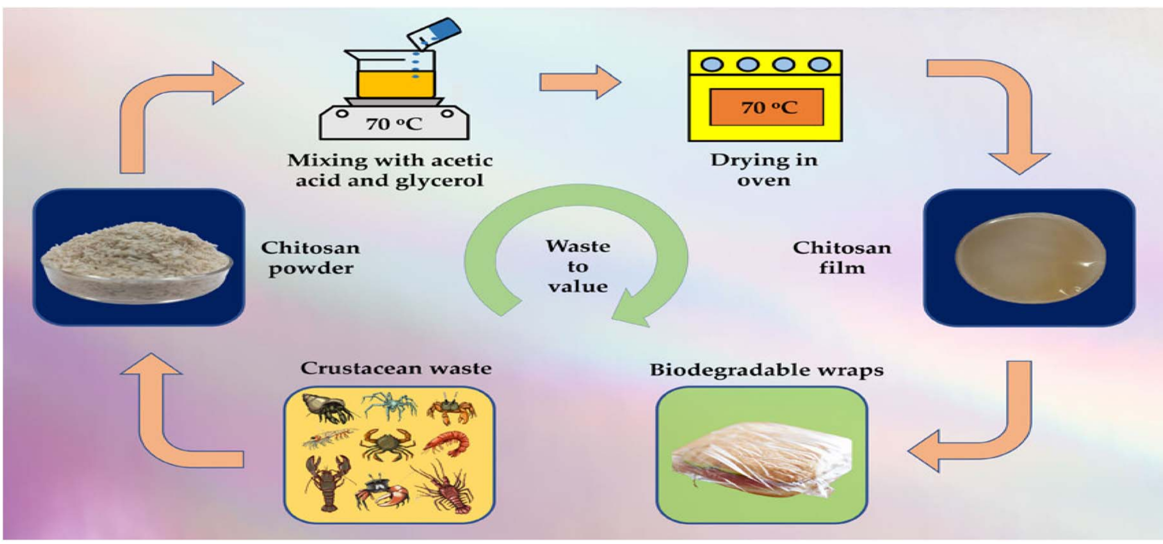

Fig. 44 Schematic representation of synthesis and use of glycerol-added chitosan films for food packaging.[384] Reproduced (adapted) with permission from ref. 384. Copyright [2023] [ACS].

composite films with enhanced mechanical strength and barrier properties against oxygen and water, making them ideal for food packaging applications. Anthocyanins, natural pigments found in plants and fruits, are utilized as pH indicators in intelligent food packaging systems due to their color-changing ability at different pH levels. Incorporating anthocyanins into polymer matrices extends food shelf life and enhances packaging. To improve antibacterial, mechanical, and barrier properties of these films, nanoparticles like nano-SiO_2, gold, silver, and zinc oxide (ZnO) are added. Among these, nano-ZnO is preferred for its cost-effectiveness, antibacterial properties, and safety in food packaging. In this study, composite films of CS/PVA blended with natural extracts and ZnO nanoparticles were developed and characterized for their physicochemical properties. The incorporation of both natural extract and ZnO nanoparticles improved the properties of the films, making them suitable for various applications including food packaging. The study explored the effects of ZnO nanoparticles and anthocyanin composition on the properties of CS/PVA films, including their morphology,

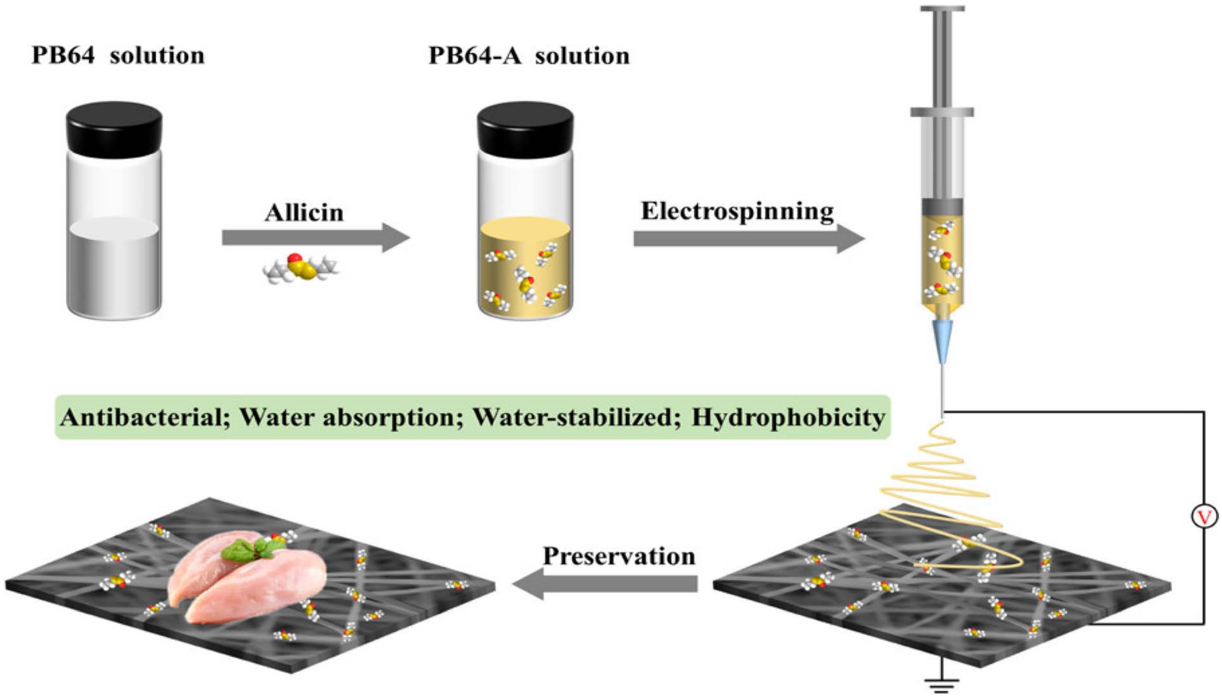

Fig. 45 Schematic representation of synthesis and use of allicin-loaded electrospun PVP/PVB nanofibrous films for food packaging.[385] Reproduced (adapted) with permission from ref. 385. Copyright [2022] [ACS].

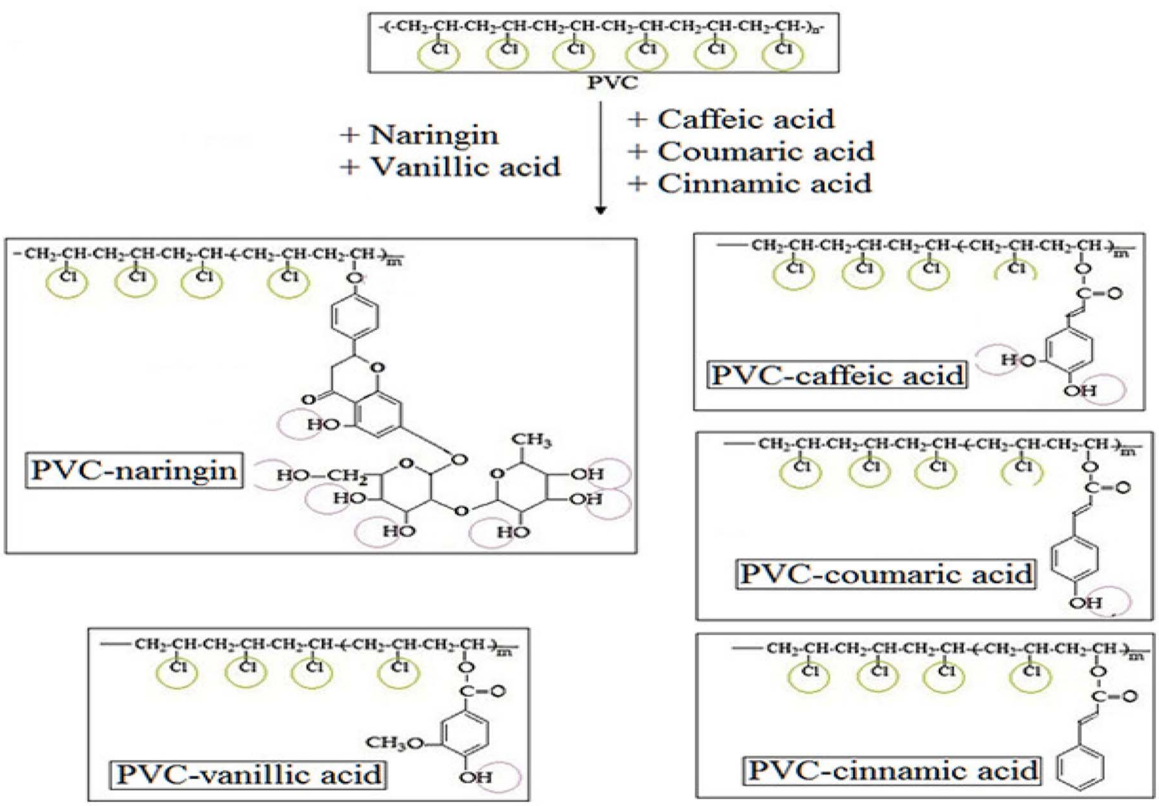

Fig. 46 Schematic representation of poly(vinyl chloride) derived food packaging materials.[386] Reproduced (adapted) with permission from ref. 386. Copyright [2023] [ACS].

mechanical strength, pH sensitivity, cell viability, and antioxidant properties. The films demonstrated potential as smart packaging materials, particularly in maintaining the freshness of fish fillets (Fig. 47).[387]

6.6. Sodium alginate–*Aloe vera* hydrogel films enriched with organic fibers

Biopolymers sourced from renewable materials, such as algae, are valuable for hydrogel production. Algal polysaccharides, notably alginate from brown seaweed, are recognized for their biodegradability and compatibility. However, pure alginate films lack mechanical strength and functional properties necessary for food packaging. Blending alginate with other polymers like *Aloe vera*, gum tragacanth (GT), and hydroxypropyl methylcellulose (HPMC) enhances their properties. *Aloe vera*, rich in water and active compounds, offers therapeutic and functional benefits. Gum tragacanth, extracted from *Astragalus* plants, is an anionic polysaccharide used in the food industry as a thickener and emulsifier. Hydroxypropyl methylcellulose, a biodegradable polymer, forms transparent, flexible, and oil-resistant films suitable for food packaging. This study builds upon previous research on alginate–*Aloe vera* composite films for food packaging. The optimal concentrations of alginate and *Aloe vera* were determined in earlier studies. Here, gum tragacanth and HPMC were added to reinforce these films. The study aims to compare the reinforcing effects of gum tragacanth and HPMC and their impact on the physicochemical and functional properties of alginate–*Aloe vera* films (Fig. 48).[388]

6.7. *In situ* crosslinked Schiff base biohydrogels containing *Carica papaya* peel extract: application in the packaging of fresh berries

Papaya (*Carica papaya* L.), a widely cultivated tropical fruit, is rich in bioactive compounds beneficial for human health. The significant amount of waste generated from papaya harvesting, mainly in the form of peels, has prompted researchers to explore its potential as a valuable resource. Papaya peels (PPs) have traditionally been used in various applications such as cattle feed and nutraceutical supplements. However, recent efforts have focused on valorizing PPs to develop value-added products, including biofuels, dietary fibers, biomaterials, and corrosion inhibitors. Starch and chitosan, important biopolymers in the food processing industry, suffer from poor mechanical properties when used individually. To address this limitation, researchers have combined these biopolymers to create hydrogels with enhanced properties. Typically, hydrogel synthesis involves chemical crosslinking reagents, but there is a growing interest in green chemistry approaches. In this study, *in situ* crosslinked Schiff base hydrogels were prepared without external crosslinkers, utilizing periodate oxidation to functionalize starch and create aldehyde groups for crosslinking with chitosan. The synthesized Schiff base hydrogels of starch and chitosan, designated as CsDAS hydrogel, were explored as potential food packaging materials. The incorporation of *C. papaya* peel extract into the hydrogels aimed to develop an active food packaging system. The study evaluated the hydrogel properties and their effectiveness in extending the shelf life of berries. This research contributes to the development of sustainable and functional food packaging materials derived from renewable resources (Fig. 49).[389]

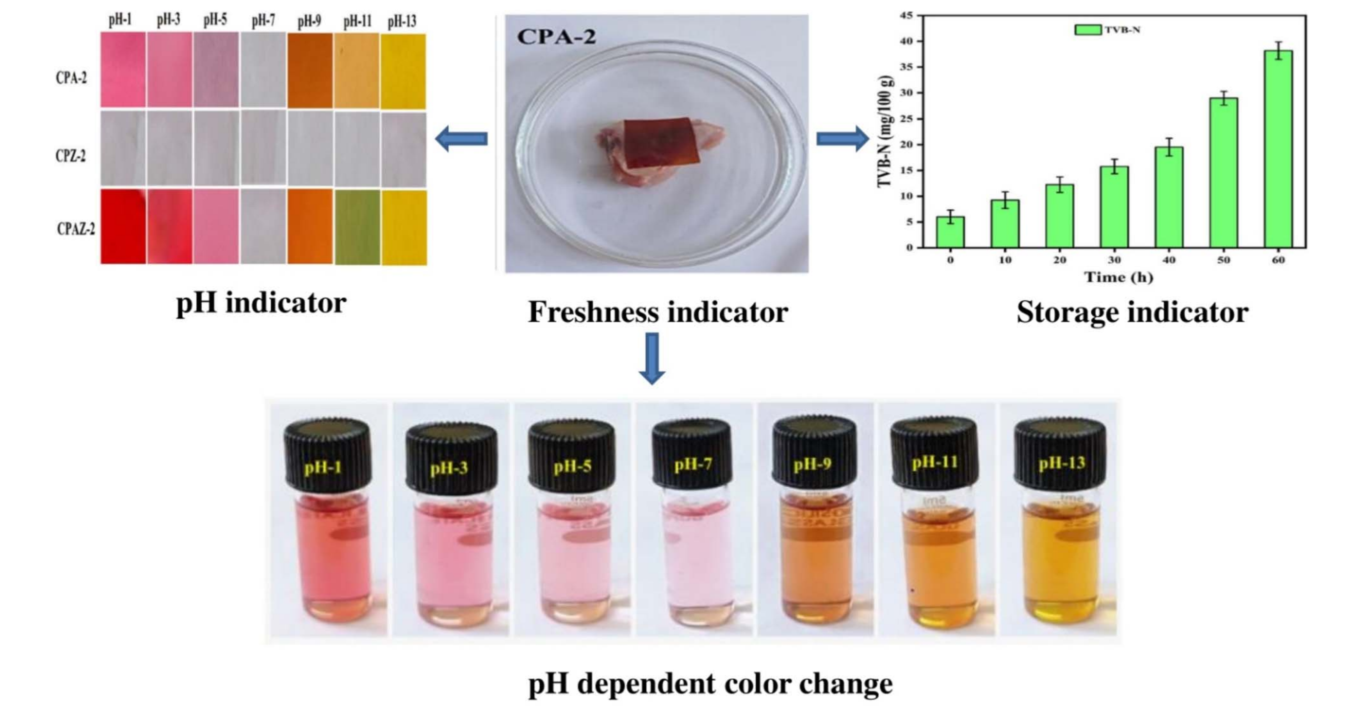

Fig. 47 Schematic representation of the use of bionanocomposite films based on chitosan/polyvinyl alcohol with ZnO NPs and *Carissa carandas* extract anthocyanin for smart packaging materials.[387] Reproduced (adapted) with permission from ref. 387. Copyright [2023] [ACS].

6.8. Gallic acid functionalized chitosan/pullulan active bio-films for the preservation and shelf-life extension of green chillies

Researchers have been exploring the development of food packaging systems by incorporating natural polyphenols such as citric acid, dextran, ascorbic acid, and gallic acid (GA) to enhance the multifunctional properties of the films. Additionally, the use of additives like green deep eutectic solvents (DES) in chitosan (CS) based films has shown improvements in solubility, tensile stability, and flexibility. Incorporating GA into CS films has been particularly effective in enhancing antimicrobial and antioxidant properties, as well as improving tensile strength and elongation at break, especially when formulated

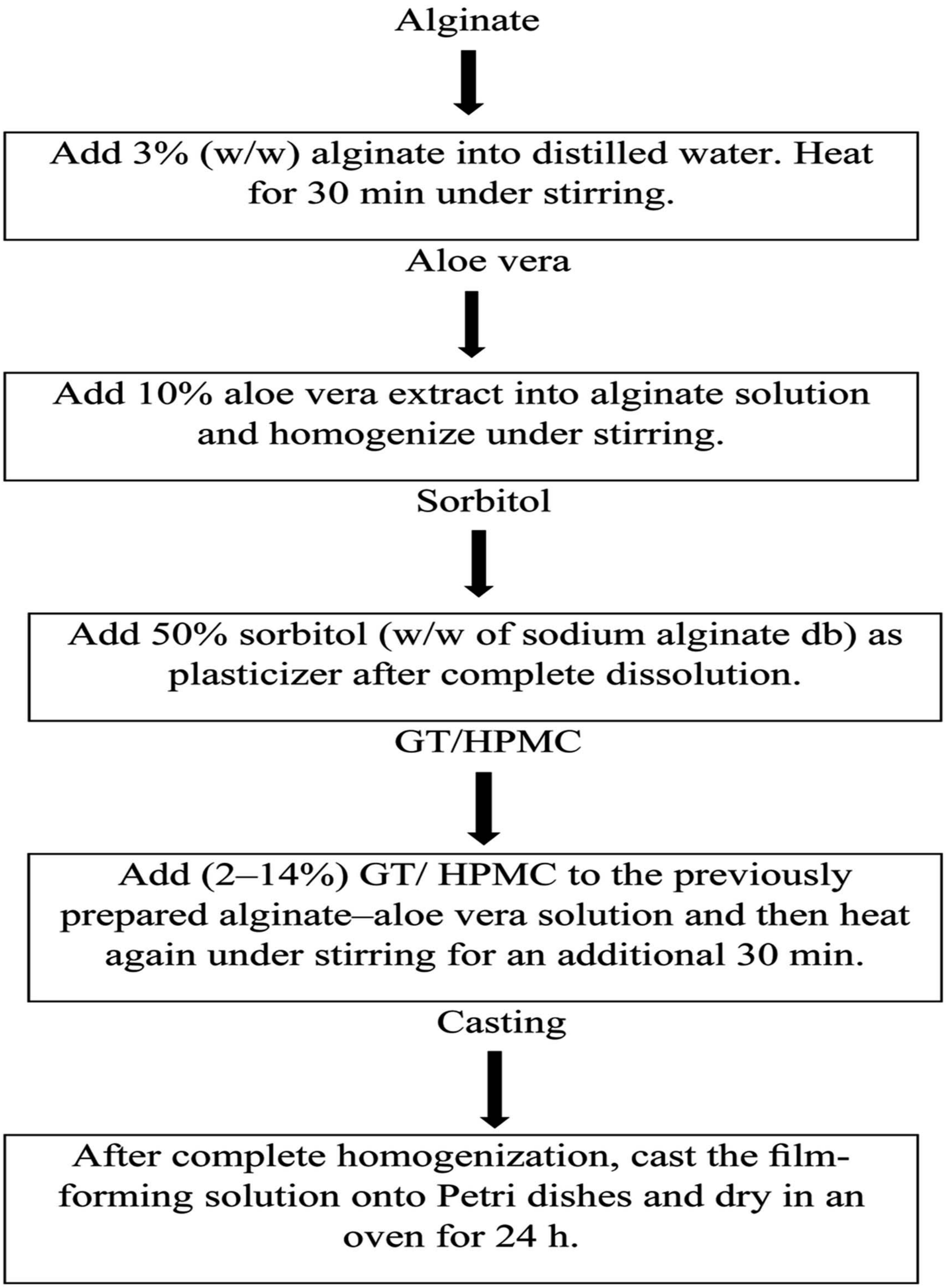

Fig. 48 Flow diagram showing the preparation of the alginate–*Aloe vera* films.[388]

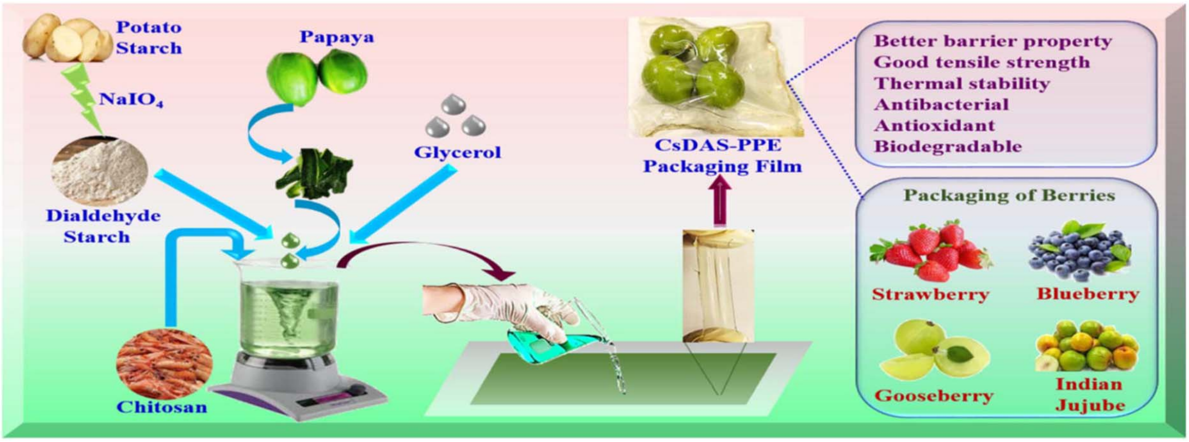

Fig. 49 Diagrammatic depiction of the fabrication of chitosan (Cs)–dialdehyde starch (DAS) Schiff base hydrogels containing *C. papaya* peel extract (CsDAS–PPE hydrogel) as novel packaging materials for fresh berries.[389]

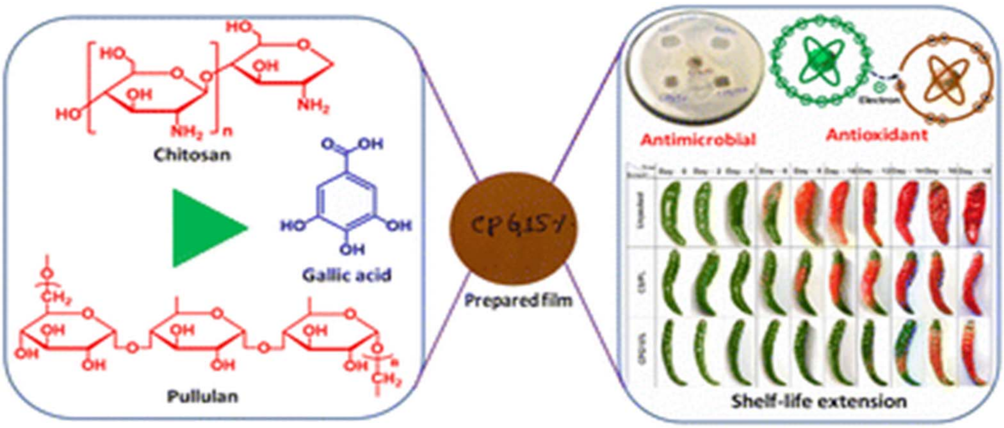

Fig. 50 Gallic acid functionalized chitosan/pullulan active bio-films for the preservation and shelf-life extension of green chillies.[390]

with gelatin. Furthermore, GA-grafted CS films have shown enhanced water vapor barrier and thermal stability. Studies have demonstrated the extension of the shelf-life of mushrooms by up to 24 days when packed with dextran-integrated CS film. These findings highlight the significant impact of using green components as additives on the functional properties of polymeric film matrices. The present study aims to develop novel CS/PL (polylactic acid) based active bio-films functionalized with different percentages of GA. The physico-mechanical and functional properties of these composite films were investigated and compared with those of pristine CS and CS/PL films. Notably, there have been no previous studies utilizing CS/PL film matrices with GA. Additionally, the research aims to evaluate the practical packaging efficiency of the developed film in preserving and extending the shelf-life of green chillies at room temperature (Fig. 50).[390]

6.9. Humidity-adjustable functional gelatin hydrogel/ethyl cellulose bilayer films

In recent years, protein films have emerged as promising materials for food packaging due to their favorable mechanical properties, cost-effectiveness, stability, renewability, and abundance. Gelatin (GEL), derived from animal processing waste, is widely used in the food industry for its excellent film-forming behavior and water-holding capacity. However, pure GEL films suffer from poor mechanical properties, thermal stability, and high water solubility, limiting their application in food packaging. Strategies such as blending with polysaccharides, essential oils, or nanofillers have been employed to overcome these drawbacks. Yet, composite films lack the ability to regulate humidity within packaging systems effectively. To address this issue, a bilayer film approach is proposed, comprising a hydrophilic internal layer and a hydrophobic external layer. Hydrogel, with its ability to absorb and retain water, serves as the internal layer to regulate humidity, while ethyl cellulose (EC) is utilized as the external layer for moisture barrier properties. Tannic acid (TA) is explored as a cross-linker for GEL hydrogel due to its cost-effectiveness and non-toxic nature. The incorporation of metallic nanoparticles, such as silver nanoparticles (AgNPs), into the film matrix provides antibacterial activity. *In situ* synthesis and immobilization of AgNPs within the GEL hydrogel network are proposed to minimize toxicity and aggregation issues. In this study, a bilayer film

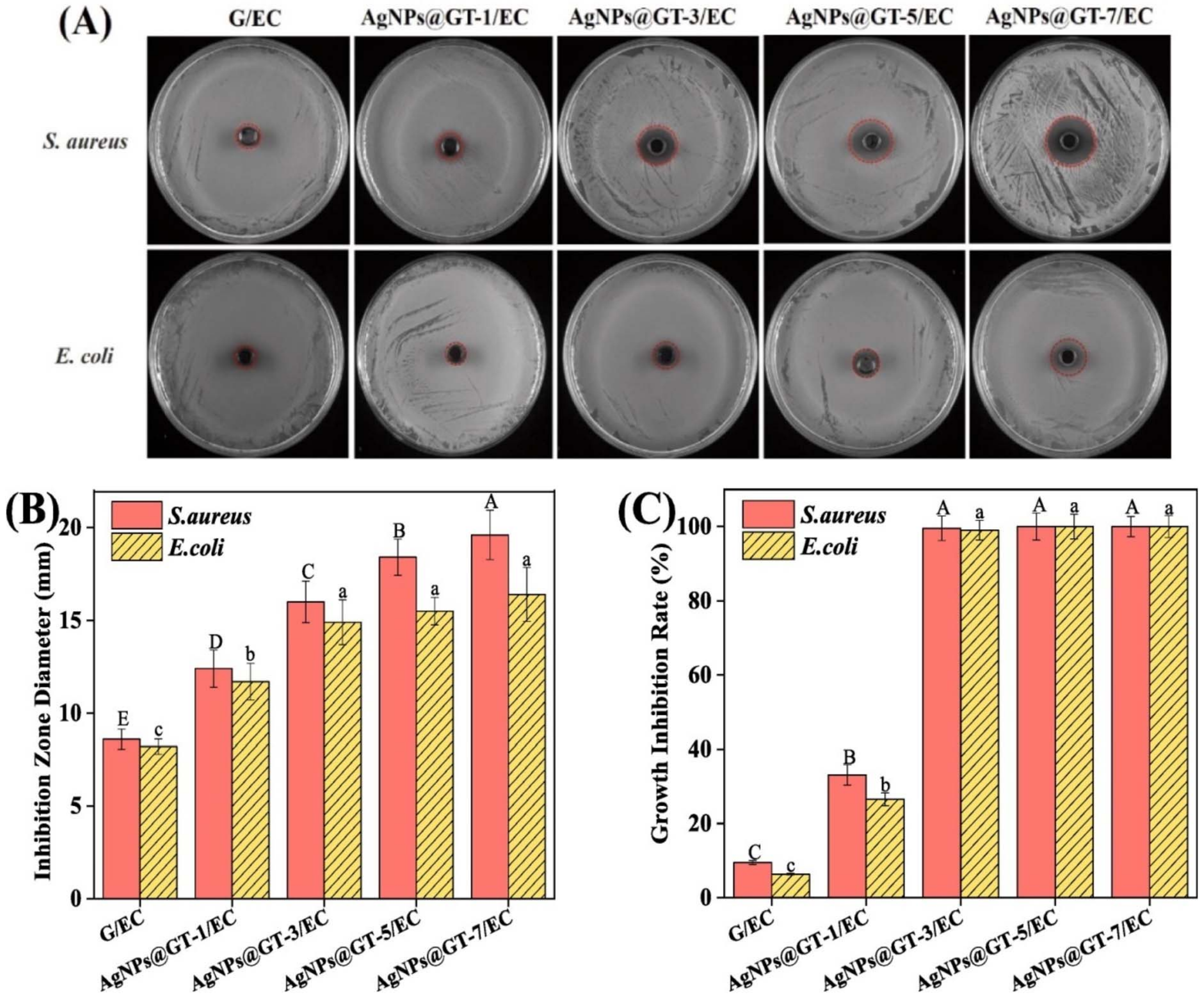

Fig. 51 Antibacterial activities of different film samples against *S. aureus* and *E. coli*: (A) antibacterial photographs, (B) inhibition zone diameter and (C) growth inhibition rate.[391] Reproduced (adapted) with permission from ref. 391. Copyright [2024] [Elsevier].

combining TA cross-linked GEL hydrogel as the inner layer and EC as the outer layer was developed. AgNPs were synthesized *in situ* and immobilized within the GEL hydrogel network to introduce antibacterial activity. The physicochemical properties, migration in food simulants, and biodegradability of the bilayer film were investigated. Additionally, the potential application of the developed bilayer film for mushrooms preservation packaging was evaluated. This research addresses the need for multifunctional food packaging materials with internal humidity regulation and antibacterial activity, which is crucial for ensuring food safety and extending shelf-life (Fig. 51).[391]

6.10. Covalent organic framework-based nanofibrous films with temperature-responsive release of thymol for active food packaging

Nanofibers are pivotal in active food packaging, with a focus on achieving rapid preparation methods for large-scale applications. Solution blow molding (SBS) has emerged as a promising technique, utilizing high-speed airflow for nanofiber production, with applications in various fields. Compared to electrospinning, SBS offers advantages such as high yield, shorter fabrication time, safety, and suitability for large-scale production. Poly(ε-caprolactone) (PCL) is commonly used for biodegradable packaging nanofibers due to its excellent mechanical properties, biocompatibility, and loading capacity. This study aimed to develop temperature-responsive active food packaging using SBS. Covalent organic frameworks (COFs) were synthesized *via* asymmetric monomer exchange (AME) for encapsulating a compound (THY), and then loaded into PCL nanofibrous films for controlled release of THY. The morphology, crystal structure, and physical properties of COFs and nanofibrous films were characterized. The release profiles of THY at different temperatures were investigated, along with the biocompatibility and antibacterial activities of the nanofibrous films (Fig. 52).[392]

6.11. Condensed tannins, a viable solution to meet the need for sustainable and effective multifunctionality in food packaging

Condensed tannins (CT) are prevalent natural phenolic polymers, ranking second only to lignin in abundance across the

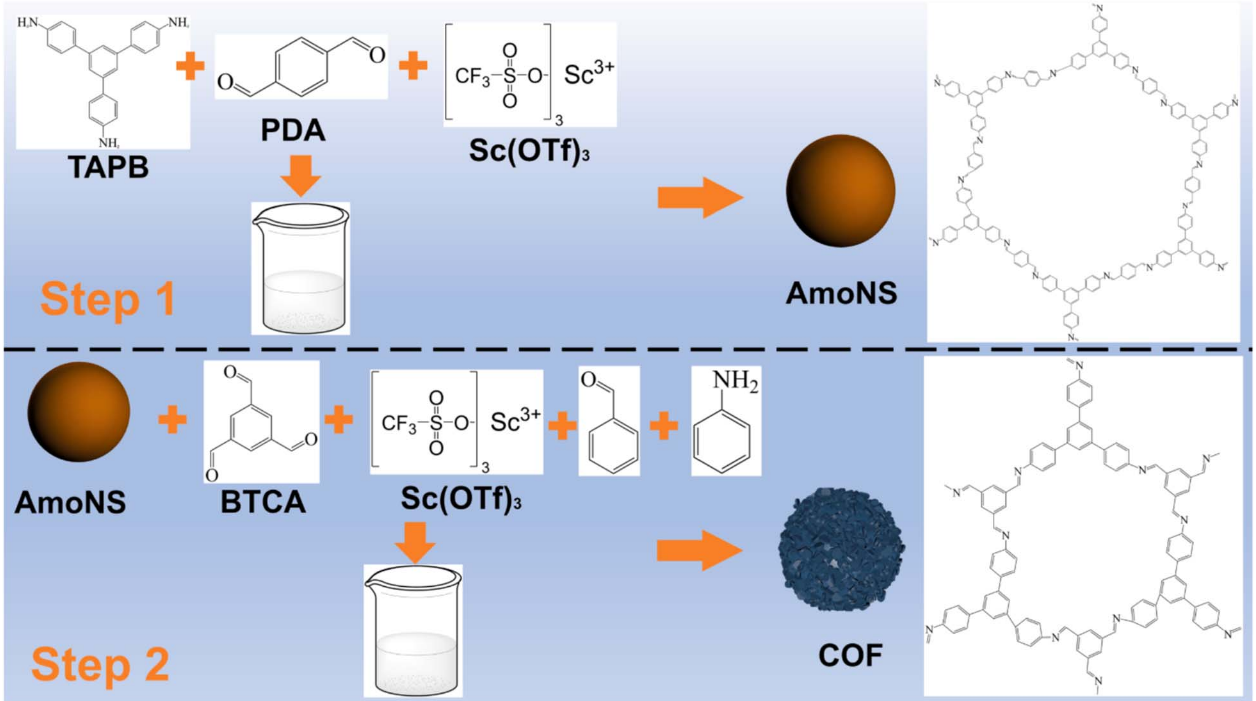

Fig. 52 The synthesis mold of AmoNS and COFs.[392] Reproduced (adapted) with permission from ref. 392. Copyright [2023] [Elsevier].

plant kingdom. They are widely distributed, with the highest concentrations found in the bark and heartwood of various tree species like mimosa, quebracho, and oak. Additionally, CTs are present in nuts, fruits, seeds, leaves, twigs, and stems of certain leguminous plants. Berries, persimmons, bananas, apples, cocoa, and grape seeds are notable sources of CT. In recent years, CTs have garnered attention as multifunctional additives in the food packaging sector. Their biocompatibility and antimicrobial properties make them effective against food spoilage, while their unique chemical properties offer advantages for functional packaging design. CTs can reinforce packaging polymer matrices, enhancing mechanical properties, UV and thermal stability, and gas permeability. Moreover, they can act as functional additives to prolong food shelf life by delaying deterioration processes. CTs' antioxidant properties stabilize materials commonly used in food packaging, such as polyolefins and polylactic acid, against thermal and photo-induced oxidation. Their ability to interact with polymer matrices improves mechanical properties and barrier properties crucial for food freshness and protection from oxidative deterioration. CTs also exhibit antimicrobial and antifungal activities against foodborne pathogens, enhancing the oxidative stability of lipid-rich foods during storage. They can prevent enzymatic browning in fruit smoothies by inhibiting polyphenol oxidases' activity and improve frying oil quality by removing toxic carbonyl species. Incorporation of CT into food packaging materials is typically achieved through techniques like extrusion, solvent casting, or vacuum filtration, without requiring chemical linkage to the polymer. Characterization methods such as microscopy, spectroscopy, and mechanical tests assess CT's effects on the packaging material's properties and performance. Several innovative applications of CT in food packaging have emerged, such as PLA films incorporating CT from pecan nut shells, whey protein-based edible films with antimicrobial properties, and chitosan-based composite films with enhanced antioxidant activity and barrier properties. Overall, CT-functionalized materials hold significant potential for improving food packaging's safety, quality, and sustainability, with various patents reflecting ongoing research and development efforts in this area.[393] Fig. 53 represents some important food packaging applications of CT.

6.12. Photothermal controlled antibacterial $Ta_4C_3T_x$–AgNPs/nanocellulose bioplastic food packaging

Currently, various antibacterial agents, including antibiotics, biological extracts, natural polymers, and metal nanoparticles, are utilized. However, the misuse of antibiotics has led to bacterial resistance, and biological extracts and natural polymers often lack strong antibacterial properties. Consequently, metal nanoparticles, particularly silver nanoparticles (AgNPs), have emerged as preferred antimicrobial agents due to their high efficiency, broad spectrum, long-term efficacy, stability, and low toxicity. Despite AgNPs' effectiveness, direct incorporation into biomass packaging materials can lead to excessive release, posing potential health and environmental risks, while also failing to provide long-lasting antibacterial effects. To address these challenges, researchers have turned to two-dimensional (2D) nanomaterials, such as MXene, for immobilizing AgNPs. MXene's large surface area makes it an ideal template for immobilizing AgNPs, preventing agglomeration and cumulative toxicity. Moreover, tantalum carbide ($Ta_4C_3T_x$) MXene exhibits excellent photothermal conversion properties, enabling controlled AgNPs release under near-infrared light. However, the binding between antibacterial agents and cellulose in composite packaging may be weak, affecting packaging performance. Quaternized chitosan (QCS), a derivative of chitosan, offers a potential solution due to its green reducing properties and structural similarity to cellulose. By serving as a reducing agent for *in situ* AgNPs preparation and a binder between MXene and nanocellulose, QCS facilitates the integration of antimicrobials into the packaging matrix. In this study, single-layer $Ta_4C_3T_x$ nanosheets were prepared from Ta_4AlC_3 and combined with AgNPs to form $Ta_4C_3T_x$@AgNPs. This antimicrobial agent was then compounded with

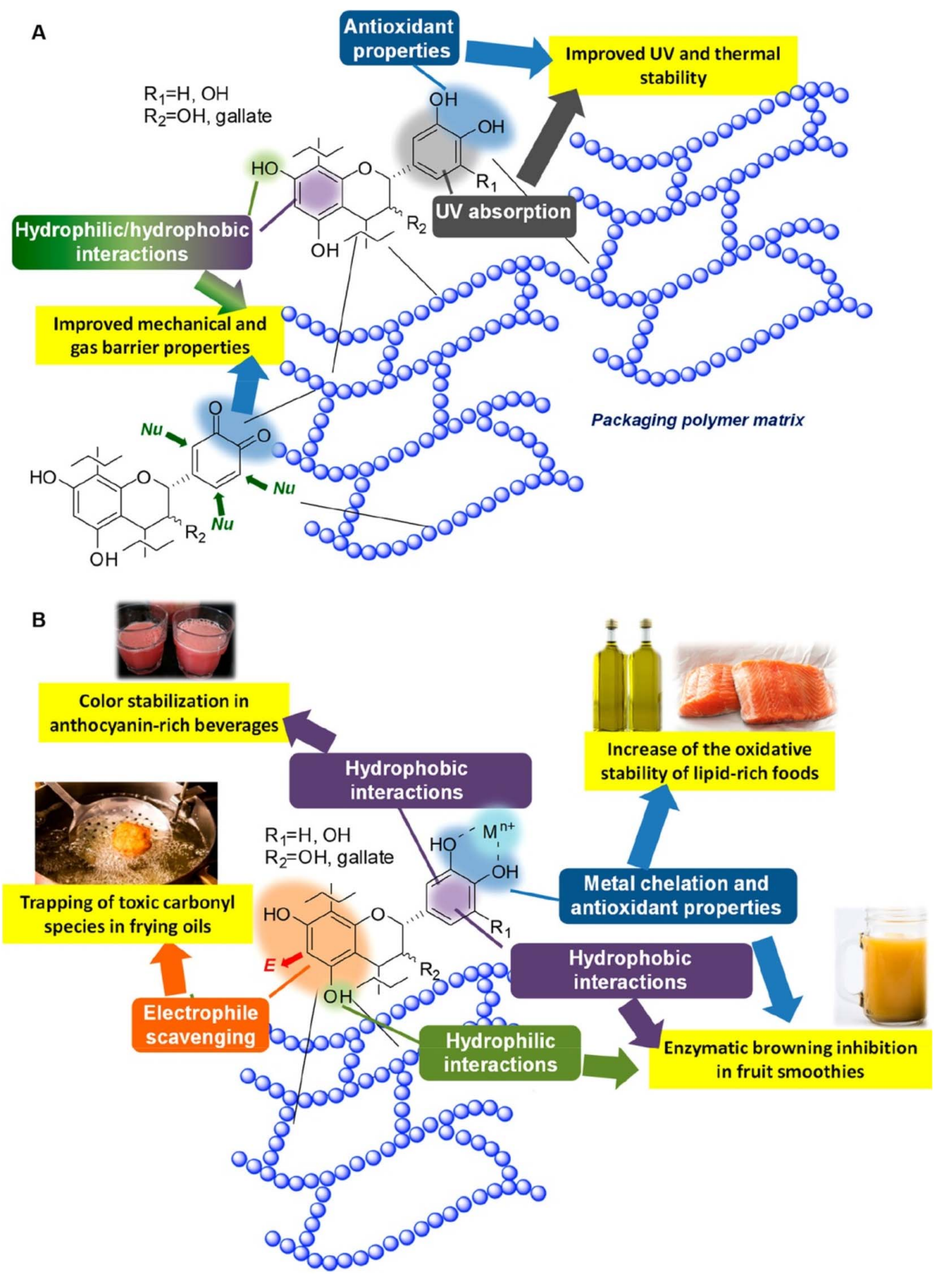

Fig. 53 Exploitation of CT chemical properties in food packaging: (A) role of CT for reinforcement of the packaging polymer matrix and (B) role of CT as functional additives able to delay the onset of deterioration processes and prolong the shelf life of food.[393]

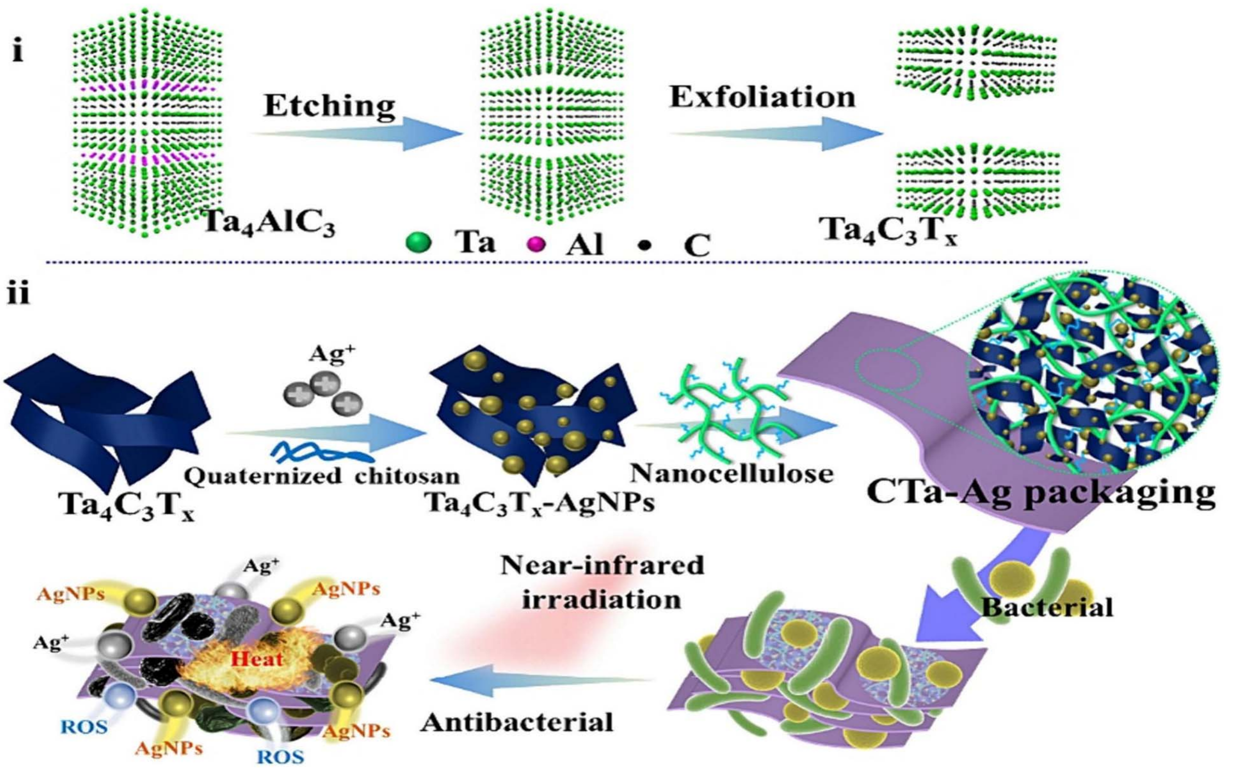

Fig. 54 Schematic illustration of (i) $Ta_4C_3T_x$ preparation from Ta_4AlC_3, and (ii) fabrication of CTa–Ag packaging.[394] Reproduced (adapted) with permission from ref. 394. Copyright [2024] [Elsevier].

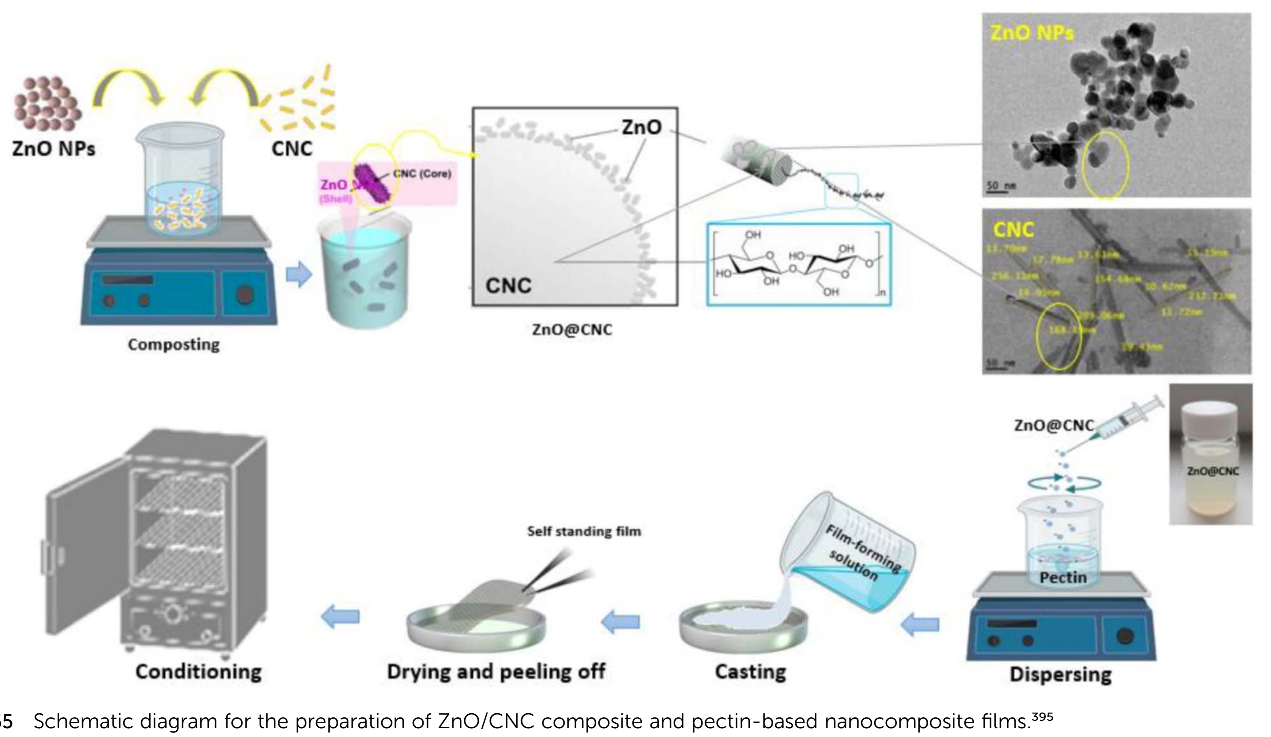

Fig. 55 Schematic diagram for the preparation of ZnO/CNC composite and pectin-based nanocomposite films.[395]

nanocellulose to produce nanocellulose-based bioplastic packaging (CTa–Ag) with enhanced mechanical and barrier properties. Additionally, CTa–Ag exhibited photothermal conversion capabilities, enabling controlled release of antibacterial agents while reducing cumulative toxicity.[394] Fig. 54 represents fabrication of CTa–Ag packaging.

6.13. Novel pectin-based nanocomposite film for active food packaging applications

Synthetic plastics, while commonly used for food packaging due to their affordability and performance, pose environmental and health concerns. Consequently, there's a growing demand for eco-friendly alternatives like biodegradable biopolymers such as gluten, gelatin, chitosan, starch, and alginate. Pectin, derived from plant cell walls, is a popular choice for packaging films due to its biodegradability, gelation properties, and non-toxic nature. However, its moderate barrier properties and high hydrophilicity can limit its use. To enhance its functionality, pectin films can be blended with other polymers or supplemented with nanosized fillers to improve their physicochemical, barrier, thermal, and mechanical properties. Crystalline nanocellulose (CNC), derived from lignocellulosic and cellulosic waste materials, is one such filler known for its high surface area, mechanical strength, and availability. Zinc oxide nanoparticles (ZnO NPs) offer antimicrobial and UV-blocking properties, approved for use in food packaging. The combination of ZnO NPs and CNC to reinforce pectin-based films, however, has not been extensively studied. In this study, active ZnO NPs/CNC/pectin-based films were prepared and characterized for their physicochemical, morphological, thermal, barrier, and mechanical properties. Antimicrobial activity was assessed both *in vitro* and in cheese samples stored at low temperatures. Additionally, cytotoxicity and migration of Zn^{2+} from the films to cheese were evaluated to ensure safety and suitability for food packaging applications.[395] Fig. 55 represents ZnO/CNC composite and pectin-based nanocomposite films preparation.

7. Concluding remarks and outlook

In conclusion, the use of sustainable food packaging materials has become increasingly important in recent years due to the negative impact of traditional packaging on the environment. The need for sustainable packaging is driven by concerns about plastic pollution, greenhouse gas emissions, and the depletion of natural resources. Sustainable food packaging materials can be made from a variety of sources, such as biodegradable plastics, plant-based materials, and recycled materials. These materials offer benefits such as reduced waste, decreased carbon footprint, and the ability to be recycled or composted. While there is no single solution to the problem of unsustainable food packaging, the adoption of sustainable packaging practices can help mitigate the environmental impact of packaging. It is essential to continue researching and investing in sustainable food packaging solutions to create a more sustainable future for the food industry and the planet. The future perspectives of sustainable food packaging materials are promising, with a growing interest in developing and adopting innovative solutions that are environmentally friendly, economically viable, and socially responsible. One of the main drivers of sustainable food packaging materials is the need to reduce waste and increase recycling. New materials and technologies are being developed to enable more efficient recycling and composting, such as biodegradable and compostable plastics, and plant-based materials. Another promising trend is the use of renewable and biodegradable materials, such as cellulose, starch, and lignin, which can be sourced from agricultural waste or other by-products, reducing the reliance on fossil fuels and virgin materials. Furthermore, the use of reusable and refillable packaging is gaining popularity, particularly in the food service industry, where it can significantly reduce waste and costs. The future also holds potential for advanced materials that are smart and interactive, such as sensors that can detect food spoilage, extend shelf life, or improve freshness, while reducing food waste and promoting food safety. Overall, the future perspectives of sustainable food packaging materials are exciting, and the continued research, development, and adoption of innovative solutions will play a critical role in creating a more sustainable and circular economy for the food industry.

The food packaging industry is constantly evolving to meet the changing demands of consumers, regulators, and the environment. Some future research opportunities in this field are:

Sustainable packaging materials: the use of eco-friendly packaging materials such as biodegradable plastics, paper, and other sustainable alternatives is increasing. Further research can focus on the development of new materials that are more environmentally friendly, cost-effective, and have improved barrier properties.

Smart packaging: smart packaging can help to improve food safety, enhance shelf-life, and provide better consumer information. Further research can focus on the development of new technologies that can help to reduce food waste, improve food quality, and enhance the consumer experience.

Nanotechnology: the use of nanotechnology in food packaging can provide improved barrier properties, better control of moisture and oxygen levels, and improved antimicrobial properties. Further research can focus on the development of new nanomaterials that can help to reduce food waste, improve food quality, and enhance the safety of packaged foods.

Food contact materials: research can focus on the development of new materials that can improve the safety and quality of food contact materials. This can include the development of new coatings, adhesives, and sealants that are more durable, resistant to degradation, and have improved barrier properties.

Packaging design: packaging design can play a crucial role in improving the functionality, usability, and aesthetics of food packaging. Further research can focus on the development of new packaging designs that can improve the convenience, portability, and sustainability of food packaging.

Certainly! While the outlined research directions are promising, it's essential to ensure a balanced approach that addresses not just technological advancements but also societal needs and ethical considerations. One direction to consider could be:

Social and cultural implications of packaging innovation: understanding how consumers perceive and interact with new packaging materials and technologies is crucial for successful adoption. Research in this area could explore consumer attitudes, preferences, and behaviors towards sustainable packaging, smart packaging features, and nanotechnology applications. This could involve interdisciplinary approaches integrating psychology, sociology, and marketing to ensure that packaging innovations align with consumer values and expectations while also promoting sustainability and safety.

By considering the social and cultural dimensions alongside technological advancements, researchers can ensure that future developments in the food packaging industry are not only effective but also socially responsible and widely accepted by consumers. This approach can help bridge the gap between innovation and consumer adoption, ultimately leading to more impactful and sustainable solutions in the field of food packaging.

Data availability

Data will be made available on reasonable request.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

SH is highly thankful for the fellowship under CSIR-JRF Scheme [File No.: 09/0984(15809)2022-EMR-I]. RA is highly thankful to Ministry of Education (MoE), for financial assistance through Institute fellowship. SSM is grateful to the Director, National Institute of Technology, Srinagar, J&K for basic infrastructural and laboratory facilities.

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